HYDROGEN-OXYGEN FUEL CELL SYSTEM FOR SPACE VEHICLES

R. H. Shaw* and R. A. Thompson†

Pratt & Whitney Aircraft Division, United Aircraft Corporation,

East Hartford, Conn.

Abstract

The purpose of this paper is to show how such cells are integrated into an optimum powerplant for a space mission; it will include a discussion of cell performance parameters. Because of its advanced state of development at Pratt & Whitney Aircraft, only the Hydrox‡ cell will be considered here. The Hydrox cell employs hydrogen and oxygen reactants, dual porosity nickel - nickel oxide electrodes, and aqueous potassium hydroxide electrolyte. The use of metallic electrodes permits operating temperatures in the range of 400 to 500°F. These temperature levels result in the high power densities necessary for low powerplant weight and in heat rejection temperatures compatible with earth and lunar thermal environments.

Introduction

A fuel cell is a device for the direct conversion of chemical energy into electricity. Two reactants, a fuel and an oxidizer, are supplied to the cell to be consumed in an electrochemical reaction for the production of electricity. Thermal efficiencies of over 70% are feasible with fuel cell powerplants.

As the scope of space operations increases towards extensive earth-orbiting and lunar missions, the hydrogen-oxygen fuel cell, by virtue of its high thermal efficiency and water production, becomes the most practical means of electrical power

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*Project Engineer.

†Assistant Project Engineer.

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generation. Most of the technical literature to date has dealt with the electrochemical phenomena of a single fuel cell.

Cell Concept and Performance

Cell Concept

The heart of any fuel cell powerplant is the cell itself. One Pratt & Whitney Aircraft concept is shown schematically in Fig. 1. A disc-shaped cell results in the most compact configuration. Several features of the cell are apparent.

1) Between the dual porosity nickel electrodes is the electrolyte whose expansion and contraction is contained at essentially constant pressure by an expansion device shown schematically as a bellows in the Fig. 1. The use of a dual porosity electrode permits nominal changes in reactants-electrolyte pressure differences without substantially changing the location of the reaction site.

2) A seal to contain the electrolyte between the electrodes must be also an electrical insulator. Shown schematically is a seal which may typically be made from teflon.

3) A perforated nickel backup plate is used to support the oxygen electrode sinter structure. The hydrogen electrode sinter is self-supporting.

4) A heater is incorporated to provide startup heat requirements and, for very low power operation, to provide makeup heat to the cell.

5) Cell assemblies are stacked one against the other so that the electrical contact areas are mated with additional cells to build a module assembly. Because the hydrogen, oxygen, and exhaust vent to common manifolds, the cell supply lines must be insulated electrically from the manifolds.

Cell Performance

Fig. 3 shows how the net voltage of each cell varies with power density. It can be shown that the thermal efficiency of the cell is proportional to the voltage and is close to 90% at low power densities. As power density is increased, an ideal cell would remain at constant voltage. The drop in voltage is indicative of increasing losses and decreasing thermal efficiency. Progress toward high efficiency at high power is illustrated in Fig. 3. This progress results from electrode structure development. These data are for a cell temperature of 500°F, a pressure level of 15 psia, and an electrolyte concentration of 85% KOH. Cell performance is influenced by temperature, pressure, and electrolyte concentration and is discussed below.

The relative power density for a given load varies with cell temperature as shown in Fig. 4. The data are for a cell at a pressure of about 15 psia with an electrolyte concentration of 85% KOH throughout the range of cell temperatures. At a given current density the power density decreases with temperature. This effect is less pronounced at low current densities, which suggests that the operating temperature may be low at low powers. It is clear that the best operating temperature at high current densities is at least 500°F and probably higher. Limitations of seal design and materials currently prohibit operation at higher temperatures.

The effects of pressure and electrolyte concentration on the power density of the cell will now be examined. The performance variation with electrolyte concentration and cell pressure for a cell operating at 500°F and 150 amp ft^2 is indicated in Fig. 5. At any given concentration there is a performance increase with increasing pressure. In general it has been found that the powerplant weight-to-power ratio is minimum at a pressure level of about 4 atm.

Typical Fuel Cell Powerplant

To integrate properly an assembly of cells into a powerplant it is necessary to examine in some detail the requirements for removal of water and waste heat. Although these are accomplished simultaneously, it is convenient to discuss the requirements separately.

Water Generation

Water is generated within the hydrogen electrode in the vicinity of the interface between the fine pore and the coarse pore structure of the sinter as shown in Fig. 6. At this interface the reaction is considered to be monatomic hydrogen plus a hydroxyl ion producing water, electrons, and heat. Since water is produced on the hydrogen side of the cell, hydrogen is used to absorb the water for removal. Excess hydrogen passes through the cell picking up heat and water, and some is absorbed within the electrode structure to provide the reaction. The water will be in the form of vapor.

Water Removal Requirements

Removal of water from the powerplant eventually must be accomplished by condensation of the water vapor-hydrogen mixture. The requirements for the absorption of water by the hydrogen and the influence of these requirements on the condensing temperature will now be examined.

Water produced in this manner has been found fully to meet standards for potable water and to have a pH of approximately 6.7 and no bacteria. Circulation of excess hydrogen to remove the reaction water from the cell requires that the sum of the water into the cell plus that produced is equal to the water in the exhaust. Any two of these quantities must be chosen in a particular manner to insure the proper mass balance within the cells. To establish the relationship, an analytical model of the phenomena was adopted.

The model shown in Fig. 7 is essentially a pot of electrolyte with a semipermeable membrane (electrode) separating the electrolyte from the hydrogen. Using analytical techniques and the assumption that the hydrogen and water are in thermal and mass equilibrium with the water in the electrolyte at the exit from the cell, a relationship is found between the electrolyte concentration, the specific humidity of the inlet hydrogen, and the ratio of the hydrogen recirculated to the hydrogen consumed. Since the specific humidity of the incoming stream establishes the temperature at the end of condensation, the lines on Fig. 7 may be plotted.

It should be noted that it may be desirable to operate with a constant electrolyte volume. For a fixed cell temperature this is equivalent to a constant electrolyte concentration. To attain this it is necessary to operate with a fixed recirculation ratio and a fixed inlet specific humidity. The result of these studies is a firm understanding of the mechanism and requirements for removal of water from the cell.

Heat Generation

Heat generation occurs at the reaction sites in both electrodes and at the sites where losses occur. At power density outputs of the order of 135 w/ft^2, the thermal efficiency is about 70%, and the heat to be rejected will be about 30% of the total energy. Even with cryogenic reactant storage, the heat rejected is too large to use the reactants as a heat sink, and an external sink is required.

Heat Removal Requirements

Heat is removed from the cell by three mechanisms. The first two are radiation and conduction from the module casing; the third is convection by the recirculated hydrogen. By operating at a fixed cell temperature the radiation and conduction heat rejection are independent of the power level and may be considered fixed. The remainder of the heat rejection must be done by hydrogen cooling flow. The necessary amount of this cooling will be dependent on the power level.

Fig. 8 shows the flow and temperature level of the recirculating hydrogen required for convective heat removal. At low temperatures the flow entering the module can absorb a large amount of heat, thereby minimizing the flow rate. A low limit of temperature is indicated and is determined by the maximum expected sink temperature. As the inlet temperature approaches 500°F the required flow approaches infinity, since the temperature rise approaches zero. As the power level is varied the temperature of the recirculating flow must also vary. Because the temperatures are generally above that required for condensing the produced water from the exhaust stream, it becomes necessary to devise a system whereby the condenser can operate at a temperature lower than that allowed for module heat removal.

System Requirements

The system must provide the following functions: supply reactants, condense and remove water external from the cells, absorb water and heat from the cells, and regulate module temperature. The system shown in Fig. 9 has been devised to allow condensation of product water at low temperatures and yet to provide module cooling flow at elevated temperatures. A regenerator between the module and heat sink exchanges heat between the module exhaust and module inlet flow. It should be emphasized that the regenerator is necessary only for systems having large variations in power level.

The reactants are supplied under pressure to the reactant pressure regulators. These provide the fuel cell with hydrogen and oxygen at proper pressure to maintain the correct interface between the electrolyte and the reactants within the electrodes. A surplus of hydrogen is recirculated to remove the water formed in the reaction and also to remove the waste heat. This recirculating gas leaves the fuel cell and passes through a regenerator to a condenser radiator, where the waste heat is radiated to space. A major portion of the water vapor carried from the fuel cell is condensed and carried by viscous forces to the separator. A separator utilizing centrifugal forces separates the liquid water from the gas and forces it into a water storage system. The recirculating hydrogen containing some water vapor is pumped back to the hydrogen inlet of the fuel cell through the regenerator. If the returning gas temperature is too low, flow can be diverted around the regenerator by a control that senses module temperature.

Environmental Considerations

To insure proper functioning of the complete fuel cell powerplant system throughout any space mission, an analysis must be made of each step in the mission profile from ground test, through launch, earth orbit, to planet or space rendezvous, and return. Limiting conditions of temperature, shock, acceleration, and radiation must be considered for each component as it affects the design. Selection of materials, orientation of components, cycle selection, and operating modes must be adjusted to provide inherent compatability with the vehicle and its mission. A typical mission, such as a manned lunar surface exploration, would involve eight distinct environments: 1) earth surface, 2) earth launch, 3) earth orbit, 4) deep space, 5) lunar orbit, 6) lunar landing, 7) lunar surface, and 8) lunar launch.

Studies have shown that the problems associated with Van Allen and particle radiation, mechanical loading, and hard vacuum should be solved with conventional design techniques. The most severe environment imposed on the powerplant is the extreme range of thermal radiation sink temperatures. The magnitude of this change for a lunar mission is about 600°F.

Studies have shown that a condenser/radiator, as shown in Fig. 9, of a fixed size is not capable of rejecting heat in a lunar orbit or on the lunar surface without freezing in deep space.

The desire to match the fuel cell powerplant to the extremes of sink temperatures with a fixed heat rejection area requires an intermediate fluid loop between the powerplant and the environment. Furthermore, the fluid loop must be capable of cooling the powerplant exhaust to remove the waste heat and condense the correct amount of water while operating over a range of sink temperatures. One such system is shown schematically in Fig. 10.

A fluid is circulated through the condenser and absorbs heat from the hydrogen-water vapor flow. This flow passes through a regenerator to adjust the fluid temperature in the radiator to the heat sink requirements. From the regenerator the flow circulates through the radiator, some is passed back through the regenerator, and the remainder bypasses the regenerator. The regenerator and bypass serve to cool the fluid to temperature limits required by the heat rejection characteristics of the radiator and to heat the fluid to the temperature required by the condenser. The amount of bypass is controlled by the condenser temperature. An accumulator is used to maintain acceptable pressure levels. An electric motor driven pump is required to circulate the fluid.

Many alternate systems have been evaluated including a water boiling system and a staged hydrogen circulating radiator. The forementioned system is desirable because of the following advantages: 1) the system satisfies the heat rejection requirements of the fuel cell; 2) the radiator area is fixed; 3) water boiloff is not required; 4) the system will operate in deep space, in a lunar orbit, or on the lunar surface with random orientation; 5) the required fluid temperature levels are compatible with the favored working fluid; and 6) control is simple.

The working fluid should feature: 1) temperature stability for long life, 2) compatibility with structural metals for long life, 3) low viscosity and high specific heat for low pumping power, 4) high thermal conductivity for minimum radiator area, and 5) low vapor pressure for minimum structure weight. A glycol-water mixture is one fluid that exhibits satisfactory features.

Optimizing the Space Powerplant

Finally, the optimum design of a powerplant of the type discussed here will be considered. Powerplant optimization requires a knowledge of the desired balance among system reliability, weight, performance, and other characteristics of importance to the mission. A full discussion of these items, however, is beyond the scope of this report. Only those optimizations involving the balance between dry weight and reactant weight (performance) to obtain the minimum overall weight will be considered here.

Such optimizations require a knowledge of factors such as maximum and minimum power and voltage levels and mission duration as well as environmental conditions. These factors in turn depend on the mission objectives, where the spacecraft is going, how long it will take, how it is getting there, etc. Because of the difficulty in generalizing these factors, typical requirements for a lunar landing mission have been selected. These are shown in Fig. 11.

The primary design parameters that enter into the optimization are 1) cell temperature, 2) cell pressure, 3) cell current density.

1) Cell temperature: Cell performance gains above 900°F have been shown to be negligible, and operation above 500°F is not required. The effect of temperature on dry weight is negligible in the operating range of 300 to 500°F. Consequently, minimum powerplant weight will occur at a cell temperature of about 500°F.

2) Cell pressure: Cell performance also will improve with increases in system pressure level. However, there is a maximum pressure beyond which the overall system weight will increase (increased hardware weight offsetting increases in allowable power density). Minimum system weight and radiator size occur at 60 psia gas pressure. The 60 psia pressure allows operation at high condensing temperatures and hence smaller radiators.

3) Cell current density: Current density is the major variable that determines system weight. For a particular mission a value may be found which will minimize the sum of powerplant and reactants weight at any point in the mission. Low current densities imply large and hence heavy cells and low reactants consumption. High current densities result in a small module size but relatively high reactants consumption.

Voltage and overload requirements impose limits on the range of operating current density. This is presented in Fig. 12, 13, and 14 for the particular requirements and shows the limiting current density as 120 amp/ft^2. For this condition the current density at the overload condition is 300 amp/ft^2. Figures 15 and 16 show the reactant consumption and system voltage at the various power levels for a system that operates at the 300 amp/ft^2 overload condition. The fuel cells provide the proper voltage regulation requirements over the normal load range.

The influence of the foregoing variables on powerplant weight are summed to establish the optimum system weight for particular mission requirements.

Conclusion

A powerplant system has been devised to satisfy the requirements of the fuel cells and the thermal environments of a typical lunar mission. The fuel cells are of intermediate temperature, dual porosity design for maximum power density and maximum heat rejection temperature. Product water and heat are removed from the cell by recirculated hydrogen flow, and potable water is condensed and separated. Temperature equilibrium, at low power, is maintained by reheating the recirculated hydrogen and water vapor with the hydrogen and vapor discharged from the cell. Waste heat is transferred from the recirculated hydrogen flow to a cooling circuit that incorporates a regenerator and a control to maintain the correct condensing temperature of the water vapor over the range of in-flight thermal environments. The system delivers electricity and water and must reject heat at about 200°F. In addition to the reactant supply, the system requires electricity for motor-pump units. Analyses of the operating modes have demonstrated the basic capability of the powerplant to perform a lunar mission.

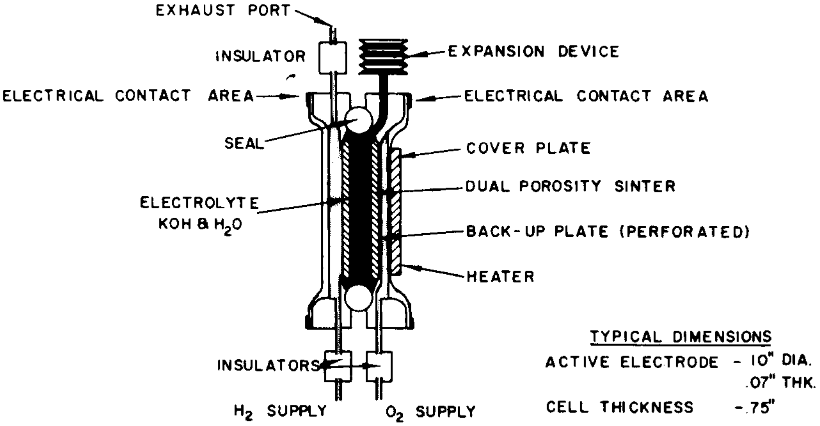

Fig. 1 Unitized cell assembly schematic

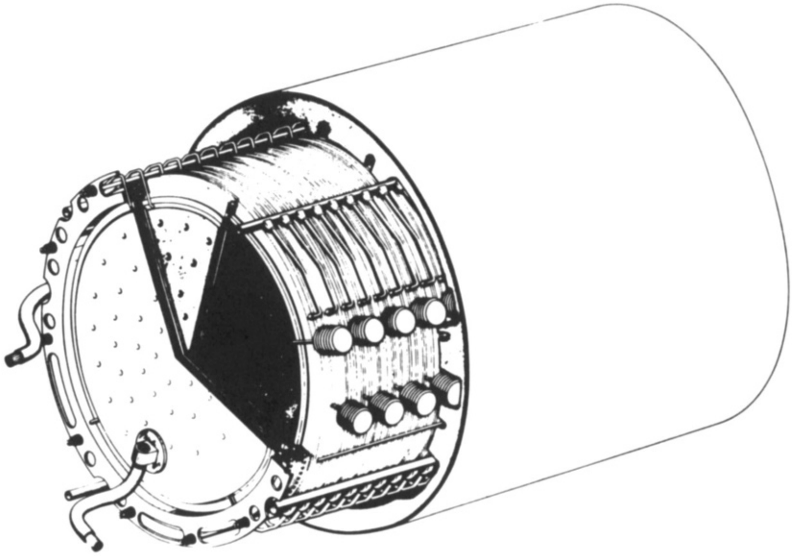

Fig. 2 Hydrox fuel cell

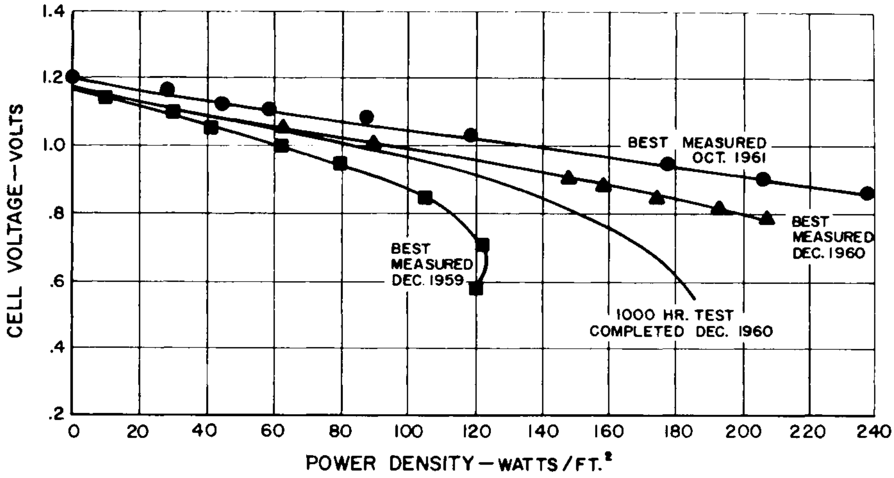

Fig. 3 Experimental cell performance; cell temperature 500°F; cell pressure 15 psia

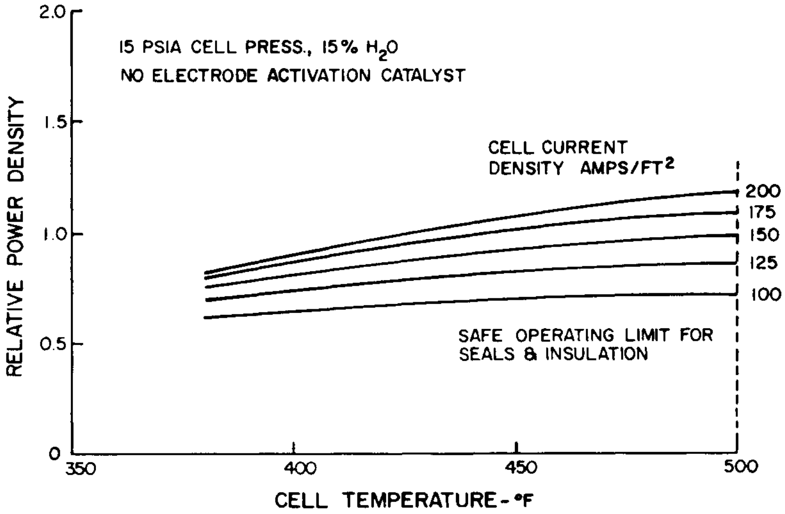

Fig. 4 Cell performance; variation with cell temperature

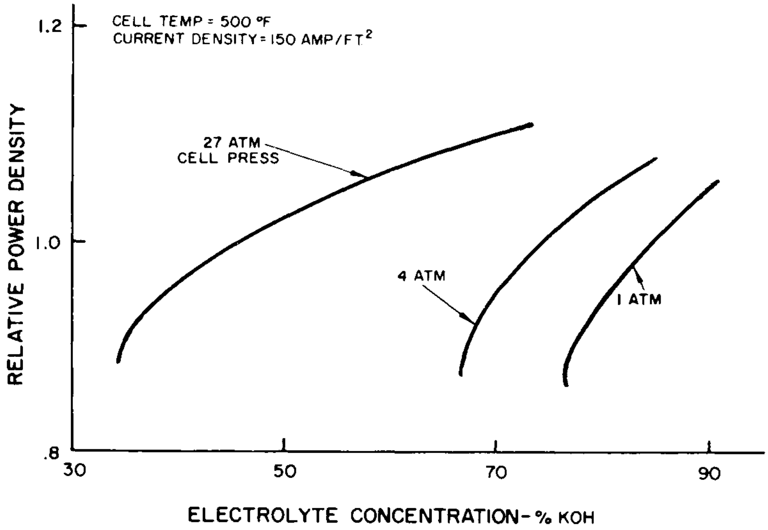

Fig. 5 Cell performance

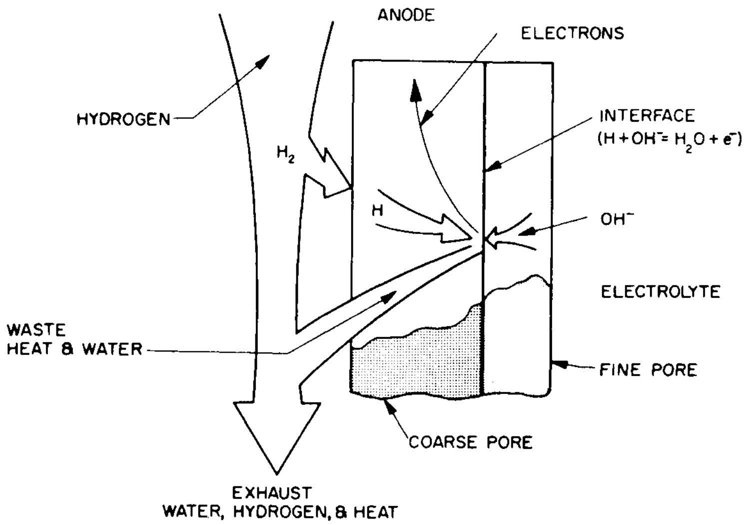

Fig. 6 Heat and water generation

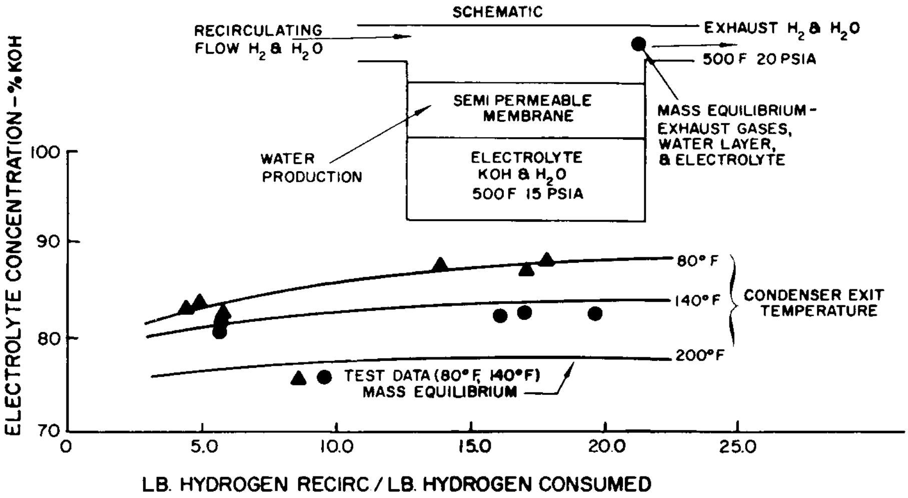

Fig. 7 Cell water removal mechanism

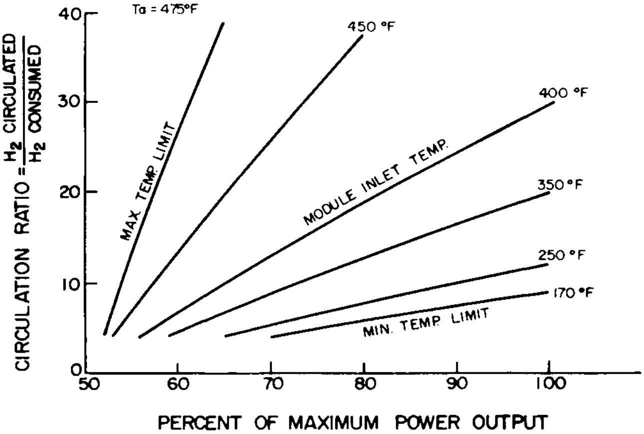

Fig. 8 Hydrogen circulation required for waste heat removal; cell temperature 500°F; constant hydrogen inlet specific humidity

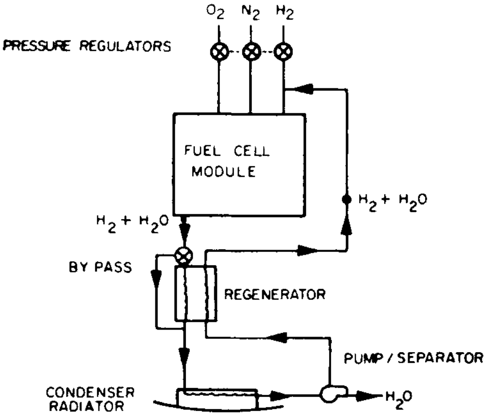

Fig. 9 Fuel cell powerplant schematic; direct condenser/radiator

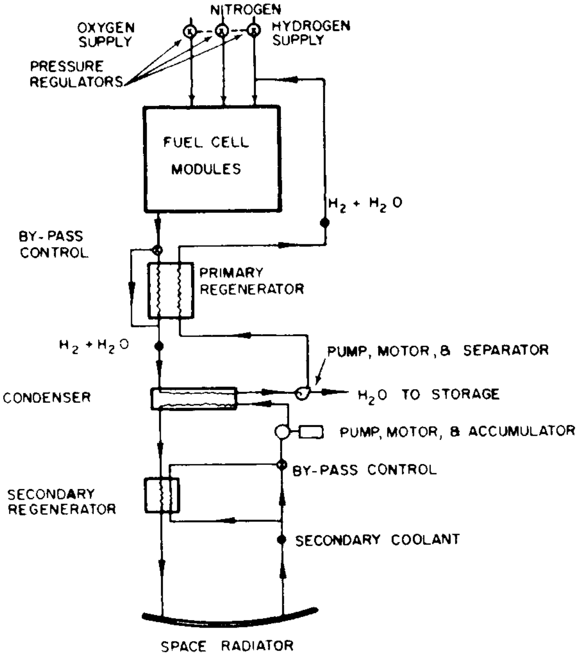

Fig. 10 Fuel cell powerplant schematic; secondary fluid radiator

RELIABILITY: COMPLETION OF A MANNED 14-DAY MISSION
THREE INDEPENDENT FUEL CELL MODULES: ANY TWO CAPABLE OF NORMAL LOAD
ANY ONE CAPABLE OF EMERGENCY LOAD

	CONTINUOUS	OVERLOAD
NET POWER, KILOWATTS	1.5 MIN. — 2.0 MAX.	3.0 MAX.
VOLTAGE, VOLTS D.C.	32 MAX. — 26 MIN.	——

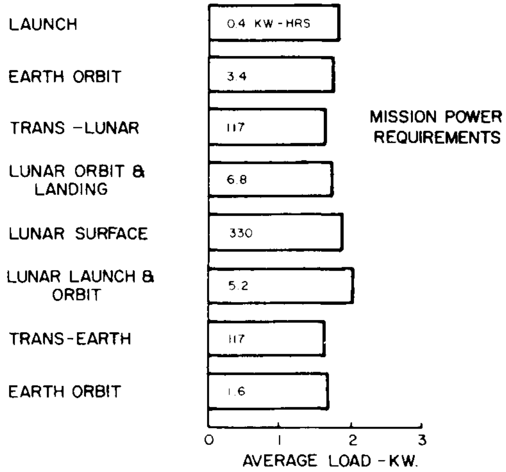

Fig. 11 Typical lunar mission requirements

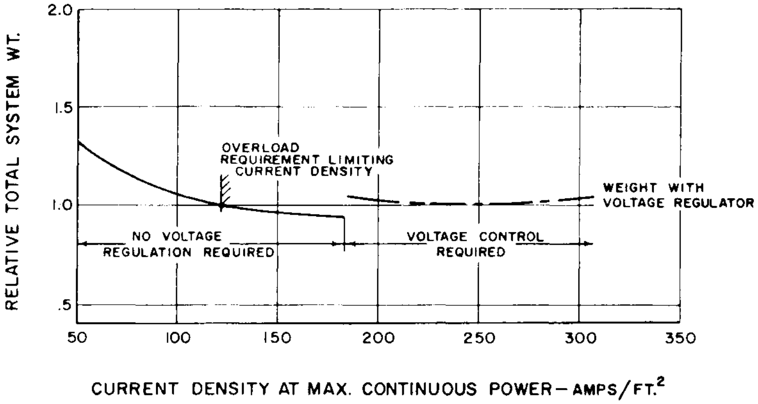

Fig. 12 Total system weight; typical lunar mission

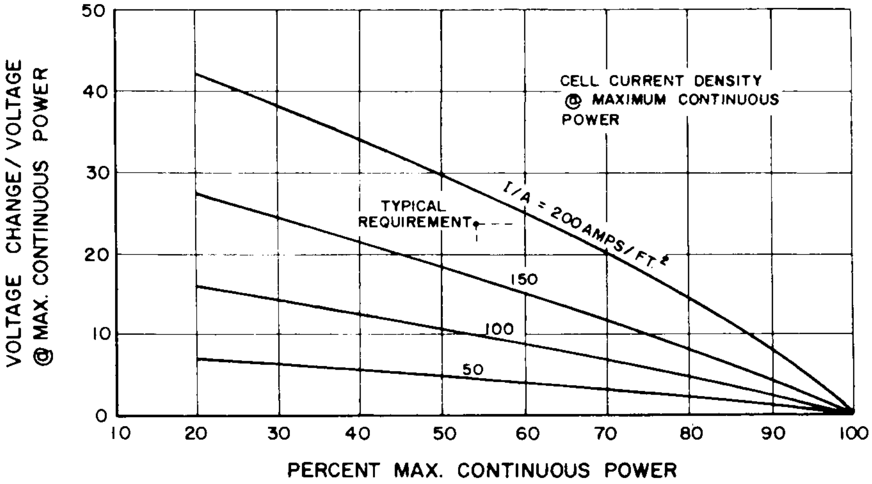

Fig. 13 Cell voltage regulation

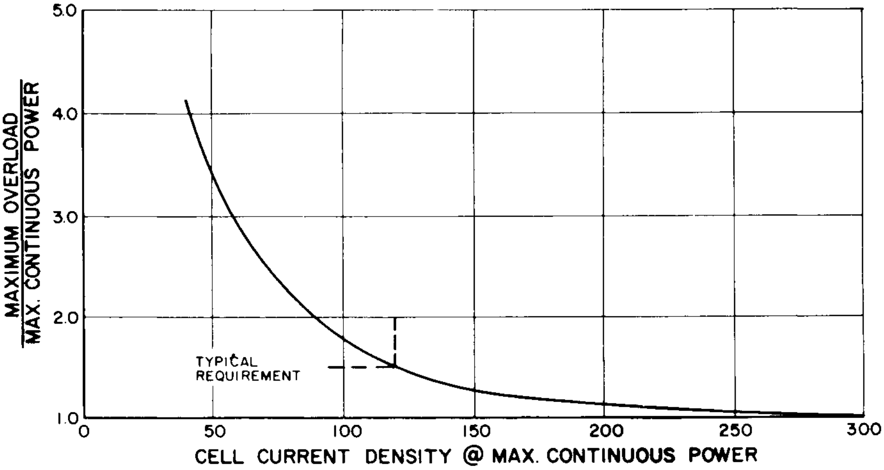

Fig. 14 Overload capabilities

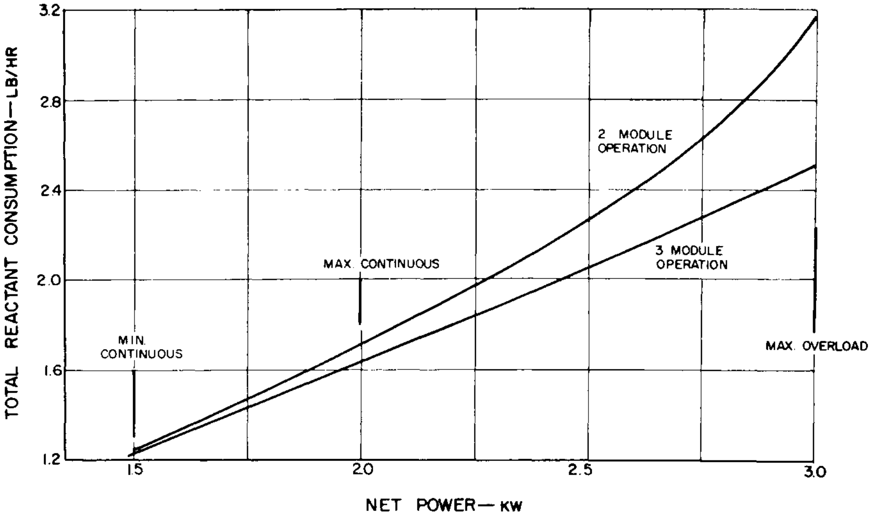

Fig. 15 Oxygen and hydrogen consumption

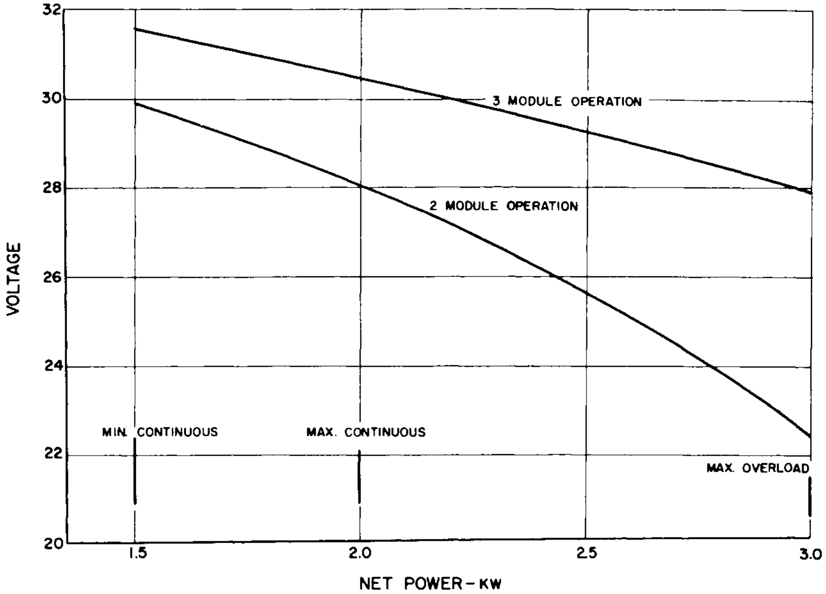

Fig. 16 System voltage