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Design Considerations for a 10-kW Integrated Hydrogen-Oxygen Regenerative Fuel Cell System

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DESIGN CONSIDERATIONS FOR A 10-kW INTEGRATED HYDROGEN-OXYGEN REGENERATIVE FUEL CELL SYSTEM

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ABSTRACT

Integration of an alkaline fuel cell subsystem with an alkaline electrolysis subsystem to form a regenerative fuel cell (RFC) system for low-earth-orbit (LEO) applications characterized by relatively high overall round-trip electrical efficiency, long life, and high reliability is possible with present state-of-the-art technology. A hypothetical 10-kW system is being computer modeled and studied based on data from ongoing contractual efforts in both the alkaline fuel cell and alkaline water electrolysis areas. The alkaline fuel cell technology is being developed under an NASA-LeRC program with United Technologies Corporation (UTC), utilizing advanced cell components and standard Shuttle-Orbiter system hardware. The alkaline electrolysis technology is that of Life Systems, Inc. (LSI), which uses a static water vapor feed technique and scaled-up cell hardware being developed under an NASA-LeRC program. This paper addresses the computer-aided study of the performance, operating, and design parameters of the hypothetical system.

INTRODUCTION

A simple schematic diagram of the hypothetical 10-kW RFC system is shown in Fig. 1. The system consists of electrolysis and fuel cell stacks, reactant storage tanks, a dual-pressure regulator, condenser, hydrogen pump/separator, and water pump. Coolant loops are located in the electrolysis stack, fuel cell stack, and condenser. Auxiliary plumbing and controls are not included.

Hydrogen, oxygen, and water are the common reactants. During the daylight portion of a low-earth-orbit cycle, the electrolysis subsystem will receive power from an external source, typically a solar array, and produce hydrogen and oxygen from water. Electrolysis occurs at high pressure, and product gases enter the storage tanks containing a fixed amount of water vapor based on the temperature, pressure, and electrolyte concentration of the electrolysis stack. A dual-pressure regulator reduces the pressure before the humidified gases are delivered from the storage tanks to the fuel cell subsystem. Here, hydrogen and oxygen react to form water during the eclipse portion of an orbit, delivering power to the spacecraft bus. Oxygen enters the fuel cell stack directly, while hydrogen enters a recycle loop downstream of the fuel cell stack. The purpose of this recycle loop is to remove product water as vapor from the hydrogen side of the fuel cell stack. The hydrogen gas leaving the fuel cell contains an amount of water vapor based on the temperature, pressure, and electrolyte concentration of the fuel cell stack. This gas stream mixes with the incoming hydrogen from the storage tank and the resulting stream enters the condenser, where its temperature is reduced and a certain fraction of the water vapor is condensed. The gas and liquid phases of this stream are separated in the hydrogen pump/separator. The gas is recirculated through the fuel cell stack to remove additional product water as vapor, while the liquid water is pumped to higher pressure and delivered to its storage tank. The cycle is repeated as liquid water enters the electrolysis stack and product gases are formed once again.

PERFORMANCE, OPERATING, AND DESIGN PARAMETERS

The goal in energy storage system design is to develop a system with an optimum combination of overall round-trip electrical efficiency, life, reliability, and both gravimetric and volumetric energy density, for the total spacecraft electrical power system for a specific mission application. The energy storage system is just one portion of the electrical power system, but its performance parameters can have major implications for the other two portions of the system; the energy conversion system and the power management, distribution, and control system. Weight is a key design criterion for the entire electrical power system. An energy storage system with high overall round-trip electrical efficiency will minimize energy conversion system weight (1) and, in the case of a solar array, lessen its area as well. This has a direct effect upon drag and reboost fuel requirements for the total spacecraft. A high voltage system will decrease the required current for a given power level and thus minimize conductor weight throughout all portions of the electrical power system. Another major design criterion is life-cycle cost. An energy storage system with long life will minimize life-cycle cost due to the reduced number of energy storage system replacements. This holds true for the other two portions of the electrical power system as well.

Performance of the hypothetical 10-kW RFC system is determined from its operating parameters; temperature, current density, pressure, and electrolyte concentration. Operating temperature and current density have the most significant impact upon energy storage system performance. Low operating temperatures will reduce chemical degradation of internal cell components and extend life, while low current densities will minimize electrochemical degradation, improve overall round-trip electrical efficiency, and also extend life (2). Therefore, high overall round-trip electrical efficiency and long life can be achieved by operating the energy storage system at relatively low levels of temperature and current density.

Energy storage system design parameters relate to system configuration and are selected to obtain maximum reliability with minimum parasitic power losses. This can be achieved through simplicity of design for thermal and fluids management, and by a reduction in the total number of ancillary hardware components. Novel integration techniques for the fuel cell and electrolyzer could also be of benefit. System design considerations include the applicable mass and energy balances which must be evaluated before final selection of proper system design parameters can be made. From a thermal management standpoint, this involves the quantity of waste heat being removed from the three separate coolant loops, its distribution to other parts of the system requiring heat at various times during a cycle, and its eventual delivery to a radiator. Thermal sharing and minimizing heat losses are of primary concern. From a fluids management standpoint, the mass flow rate of the hydrogen recycle stream in the fuel cell subsystem is a major contributor to the total parasitic power loss of the system. A condenser temperature which reduces this mass flow rate to a reasonable level is necessary. In fact, incorporation of ancillary hardware components which minimize parasitic power losses throughout the RFC system, while still maintaining reliable performance, is of paramount importance.

Evaluation of gas, electrolyte, and water management is also necessary before selection of appropriate system design parameters can be achieved. Humidified gases must always be maintained at temperatures above their respective dew points in order to avoid condensation and its inherent problems. Drying of the gases and subsequent regeneration of water vapor can thus be avoided. Electrolyte temperatures, pressures, and concentrations determine both the quantity of water vapor in the gas streams and the amount of dissolved gases in the liquid streams of the electrolysis and fuel cell subsystems. These temperatures, pressures, and concentrations must be managed properly in order to avoid evolution of dissolved gases from liquid solutions, which would necessitate gas adsorption or recombination. Taking into account the performance, operating, and design parameters, in conjunction with the appropriate mass and energy balances and gas, electrolyte, and water management techniques is a detailed and lengthy process. However, a computer program used to model the hypothetical 10-kW RFC system indicates that a system for LEO applications with an overall round-trip electrical efficiency of greater than 59 percent, life greater than 70 000 hr, and high reliability is within present state-of-the-art technology.

COMPUTER MODEL

A computer program developed at NASA-LeRC utilizing a series of variable input parameters is used to model the system. The input includes both the operating and design parameters for the hypothetical 10-kW RFC system, with performance parameters generated as output. The key operating parameters include temperature, current density, pressure, and electrolyte concentration for the fuel cell and electrolysis subsystems. The temperature and current density are assumed to be equal for each subsystem and changed for each separate run of the program. The pressure and electrolyte concentration of each subsystem are independent of one another and fixed. The major design parameter is the condenser temperature, which has a direct impact on mass and energy balances and gas, electrolyte, and water management considerations for the entire RFC system. This parameter is allowed to vary within each run of the program.

A matrix of runs is made with the computer program at various levels of temperature and current density in order to generate different values for overall round-trip electrical efficiency, life, gravimetric energy density, and volumetric energy density.

Plots of these four performance parameters versus the two operating parameters from the matrix of runs are shown in Figs. 2 to 9.

The efficiency plots (figs. 2 and 3) indicate that overall round-trip electrical efficiency increases as temperature increases, but decreases as current density increases. The temperature effect is due to improved reaction kinetics with increasing temperature. The current density effect results from larger polarization losses with increasing current density. For this matrix of runs, the efficiency range is between 43.1 percent and 66.9 percent.

The life plots (figs. 4 and 5) show that the relative life factor decreases as both temperature and current density increase. This is due to the accelerated chemical and electrochemical degradation of internal cell components with increasing temperature and current density. End of life is simply defined as the system dropping out of its specified voltage regulation range. The total life for the hypothetical 10-kW RFC system with present technology ranges between 2000 and 75 000 hr, which approximately corresponds to a relative life factor of between 0.5 and 20.0.

The gravimetric and volumetric energy density plots (figs. 6 to 9) reveal the increase in both these performance parameters with increasing current density, while temperature has little effect. Current density, as opposed to temperature, has a significant influence on the total number of cells per stack, which is reflected in the weight and volume values. For this matrix of runs, the gravimetric energy density range is from 14.8 W-hr/kg to 29.1 W-hr/kg, while the volumetric energy density range is between 5450 W-hr/m^3 and 7535 W-hr/m^3.

The total of these performance plots taken together may serve as a useful tool for selection of an optimum RFC system. For LEO applications, this system should yield high overall round-trip electrical efficiency, long life, and high reliability. Preliminary inspection of the plots reveals that for a selected case operating at a temperature of 60.0° C and a current density of 107.6 mA/cm^2, both relatively low values, the hypothetical 10-kW RFC system will have an overall round-trip electrical efficiency of 59.8 percent, life of approximately 73 000 hr, gravimetric energy density of 14.8 W-hr/kg, and volumetric energy density of 5500 W-hr/m^3 (table 1). Only the design tradeoffs remain to be performed before final system evaluation is completed.

One series of design tradeoffs involves the mass and energy balances for the system, chiefly the three separate coolant requirements and the fuel cell subsystem hydrogen recycle stream mass flow rate. Plots of these design parameters versus condenser temperature are shown in Figs. 10 and 11 for the selected case. Figure 10 depicts the coolant requirements of the electrolysis stack, fuel cell stack, and condenser. At condenser temperatures approaching the dew point temperature of the hydrogen recycle stream, 47.7° C, the recycle rate becomes so large that the fuel cell subsystem coolant requirements are borne totally by the condenser. Thus, at condenser temperatures above 39.0° C, heat would have to be supplied to the fuel cell in order to maintain its operating temperature. Similarly, at condenser temperatures below 8.7° C, heat again would have to be delivered to the fuel cell to maintain its operating temperature, in this instance due to the hydrogen recycle stream being so low in temperature. Figure 11 shows the increasing hydrogen recycle stream mass flow rate requirement with increasing condenser temperature. This flow rate becomes prohibitively large as the condenser temperature approaches the dew point temperature of the hydrogen recycle stream. These trends combine to limit the system operating range for the condenser temperature to between 8.7° and 39.0° C, where the coolant requirements are shared by all coolant loops.

Another design tradeoff involves the gas, electrolyte, and water management considerations for the system, specifically the quantity of dissolved hydrogen in the fuel cell product water once it enters the electrolysis water feed cavity. Figure 12 depicts the constant hydrogen solubility in this cavity, which is mainly a function of pressure and electrolyte concentration; and the decreasing hydrogen solubility in the fuel cell product water as the condenser temperature increases. For this selected case, hydrogen evolution from the electrolysis feed solution will not take place when condenser temperatures are above 22.9° C. The practical limit for the condenser temperature is thus in the range 22.9° to 39.0° C, where all coolant requirements and the hydrogen recycle stream mass flow rate are minimized, and dissolved hydrogen remains in solution.

CONCLUSIONS

The major requirements of any energy storage system for low-earth-orbit applications are high overall round-trip electrical efficiency, long life, and high reliability. An RFC system is able to meet these requirements through proper evaluation of system tradeoffs and final selection of system operating and design parameters. A computer program developed at NASA-LeRC used to model a hypothetical 10-kW RFC system indicates that a system with an overall round-trip electrical efficiency of 59.8 percent, life greater than 70 000 hr, and high reliability is possible with present state-of-the-art technology.

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1. R. E. MARTIN, "Electrochemical Energy Storage for an Orbiting Space Station," United Technologies Corporation, Power Systems Division, NASA CR-165436, FCR-3142 (Dec. 1981).
2. M. A. HOBERECHT, and D. W. SHEIBLEY, "Life Considerations of Hydrogen-Oxygen Regenerative Fuel Cell Systems for Energy Storage in Low-Earth-Orbit Applications," Extended Abstracts, vol. 83-2, Electrochemical Society Fall Meeting, pp. 197-198, Washington, D.C. (1983).

TABLE 1. - SELECTED CASE INFORMATION

Fuel cell subsystem	
Operating temperature	60.0° C (140.0° F)
Operating current density	107.6 mA/cm^2 (100.0 ASF)
Operating pressure	414 000 N/m^2 (60.0 psia)
KOH concentration	32.0 wt %
Active electrode area	471.9 cm^2 (0.508 ft^2)
Eclipse duration	35.7 min
Number of stacks	2
Number of cells per stack	106
Cell voltage	0.931 V
Electrolysis subsystem	
Operating temperature	60.0° C (140.0° F)
Operating current density	107.6 mA/cm^2 (100.0 ASF)
Operating pressure	2 410 000 N/m^2 (350.0 psia)
KOH concentration	25.0 wt %
Active electrode area	929.0 cm^2 (1.0 ft^2)
Daylight duration	58.8 min
Number of stacks	1
Number of cells per stack	66
Cell voltage	1.501 V
Storage tanks	
Temperature	60.0° C (140.0° F)
Regulator pressure	483 000 N/m^2 (70.0 psia)
Safety factor	1.5
Total system	
Overall round-trip electrical efficiency	59.8 percent
Life	73 000 hr
Relative life factor	18.9
Weight	401.8 kg
Gravimetric energy density	14.8 W-hr/kg
Volume	1.08 m^3
Volumetric energy density	5500 W-hr/m^3

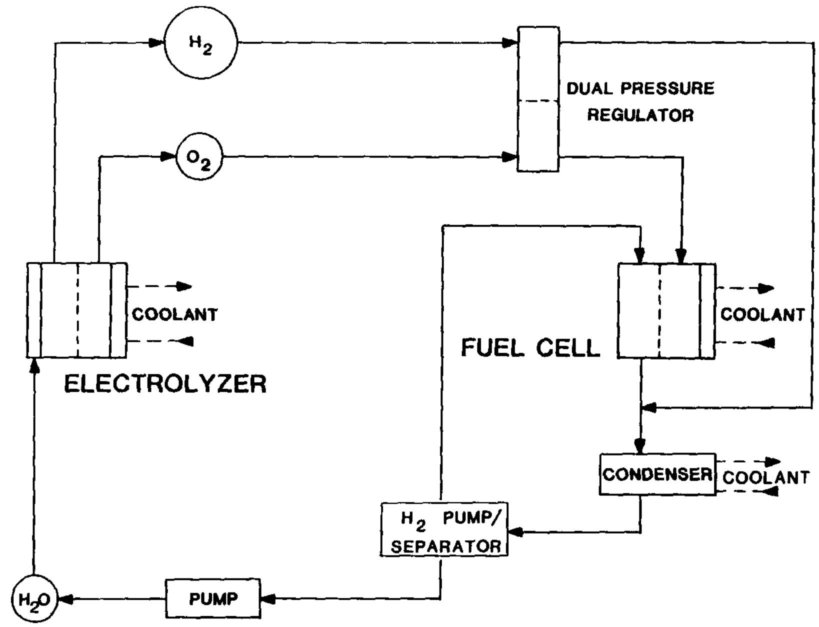

Figure 1. - RFC system schematic diagram.

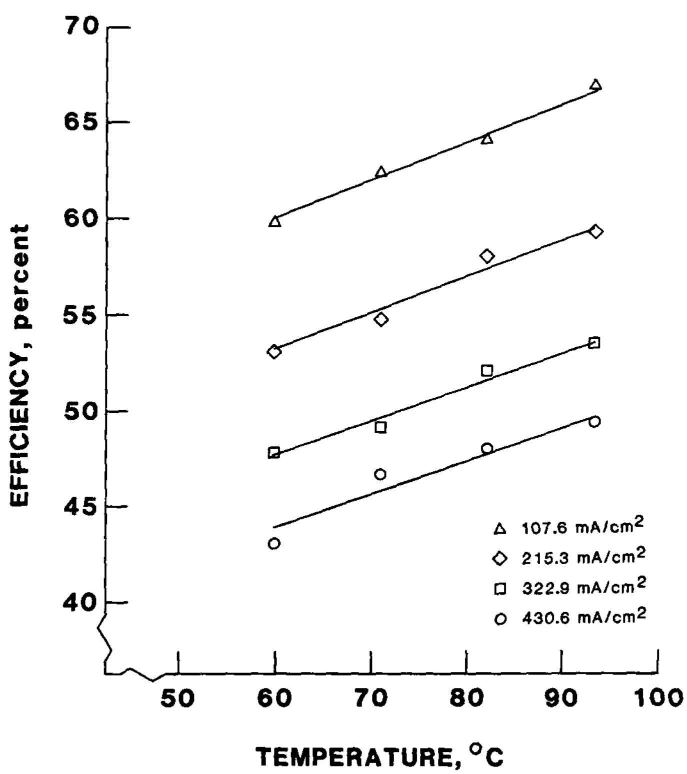

Figure 2. - Overall round-trip electrical efficiency as a function of system operating temperature.

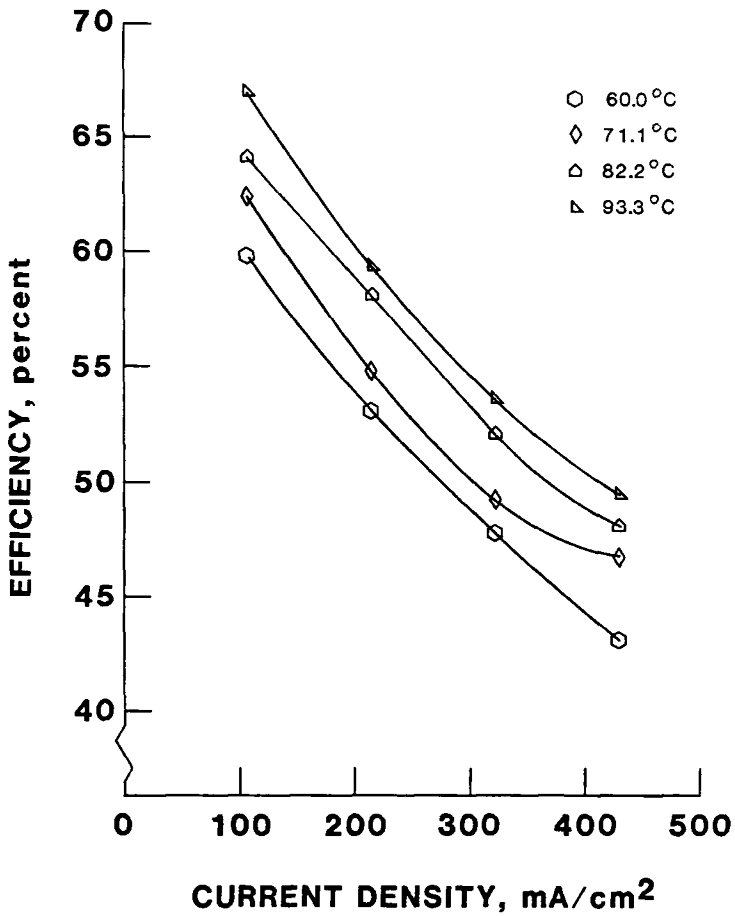

Figure 3. - Overall round-trip electrical efficiency as a function of system operating current density.

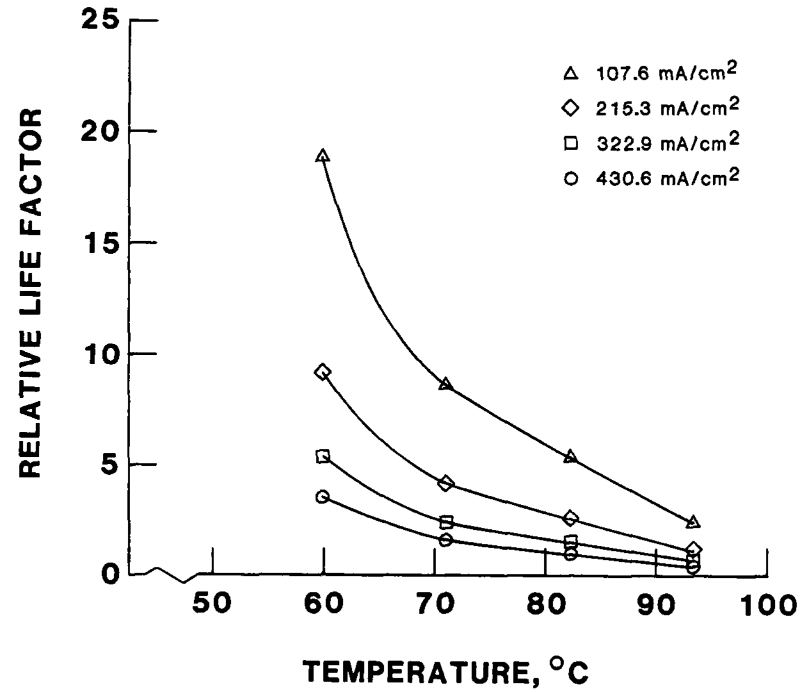

Figure 4. - Relative life factor as a function of system operating temperature.

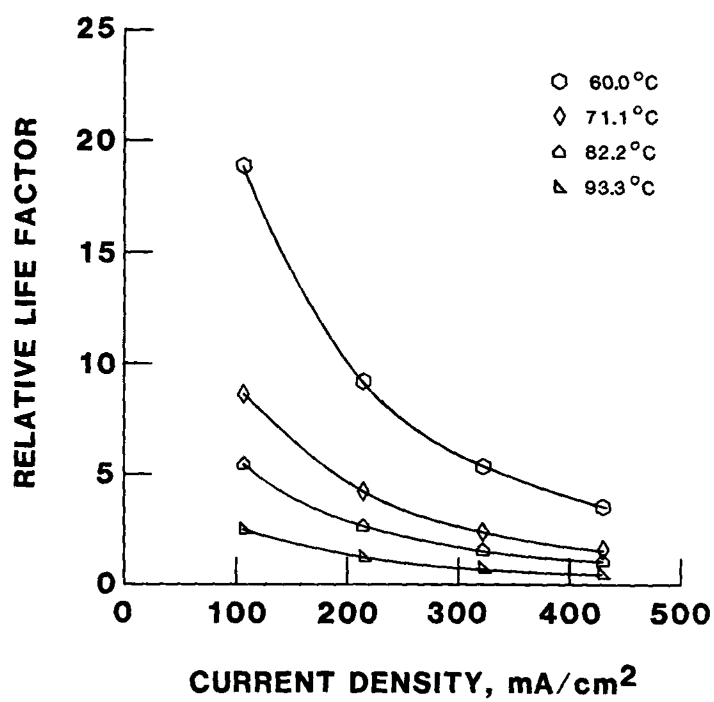

Figure 5. - Relative life factor as a function of system operating current density.

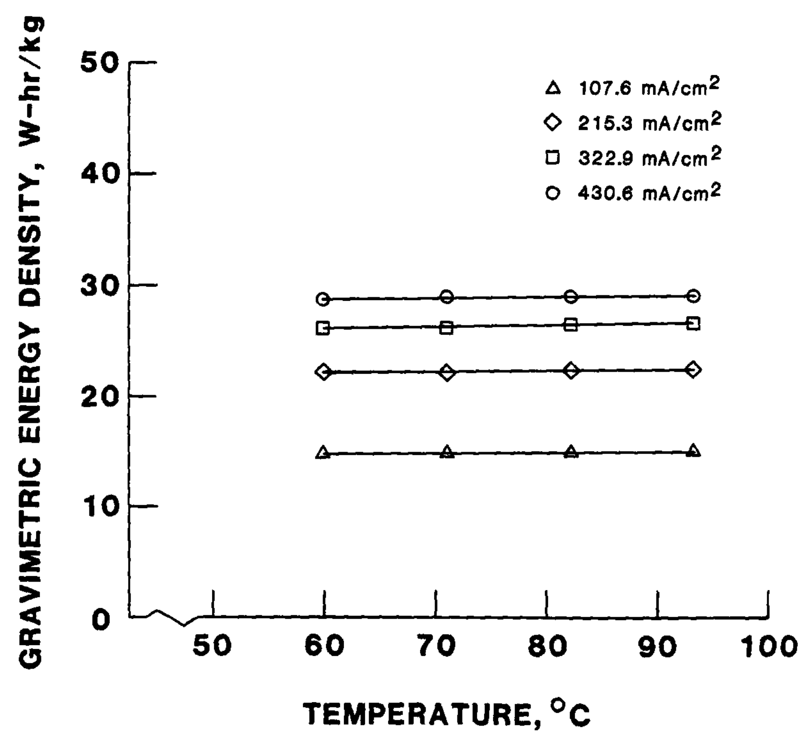

Figure 6. - Gravimetric energy density as a function of system operating temperature.

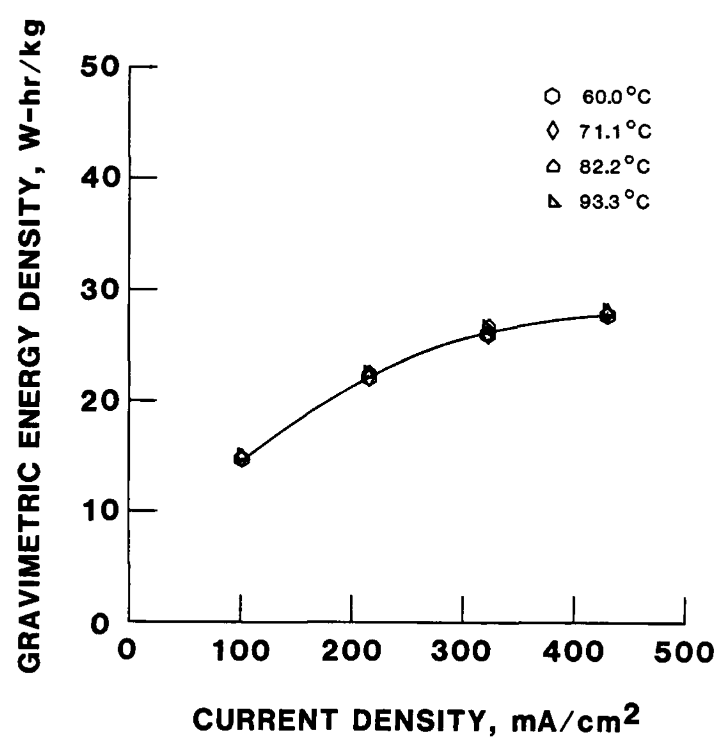

Figure 7. – Gravimetric energy density as a function of system operating current density.

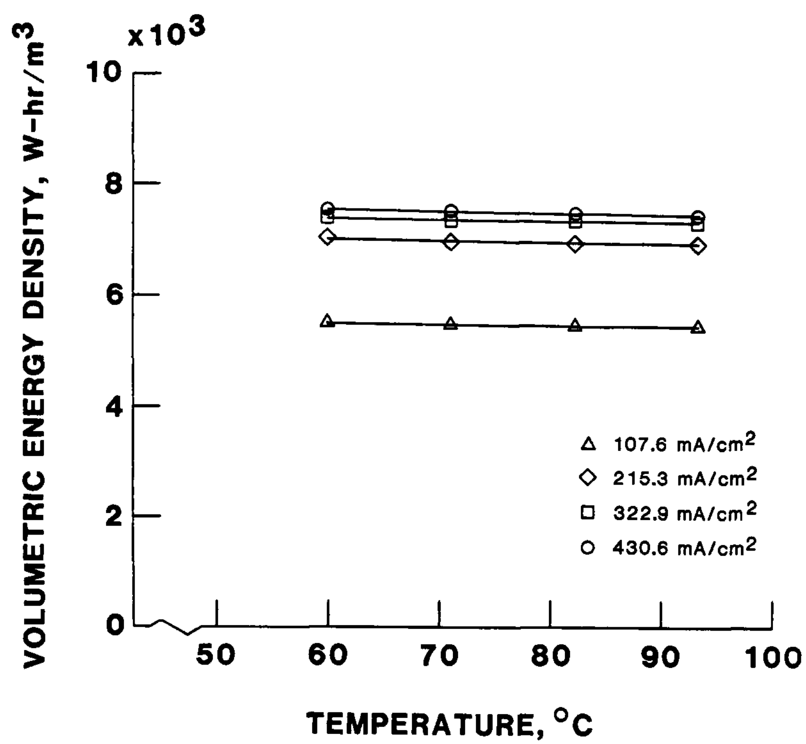

Figure 8. – Volumetric energy density as a function of system operating temperature.

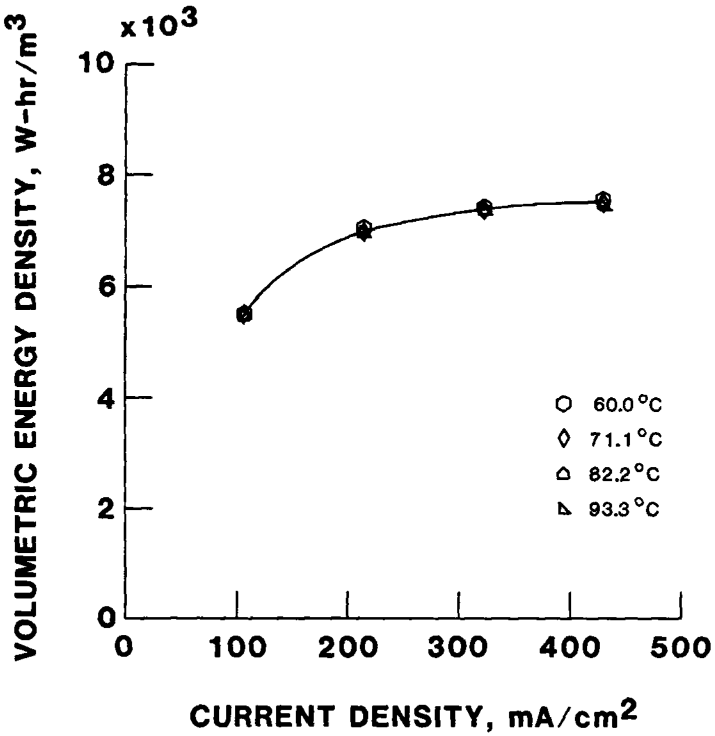

Figure 9. – Volumetric energy density as a function of system operating current density.

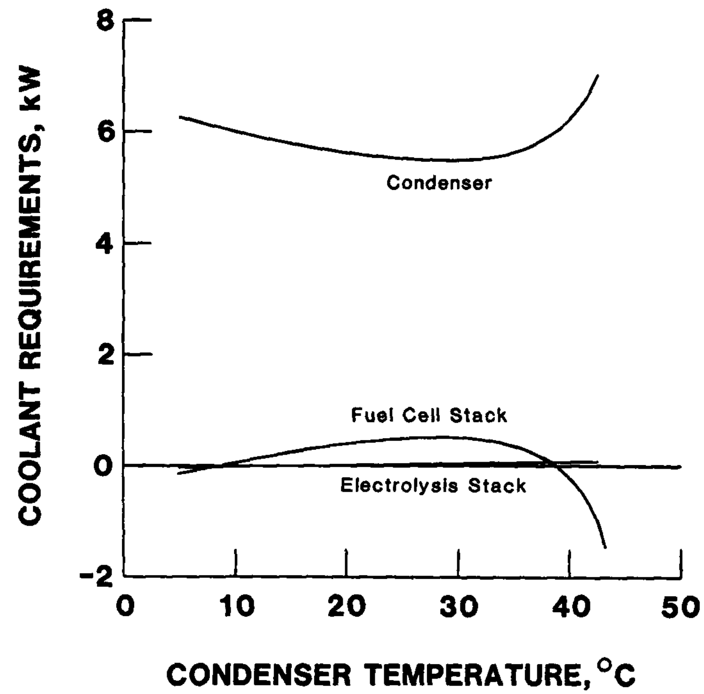

Figure 10. – System coolant requirements as a function of condenser operating temperature.

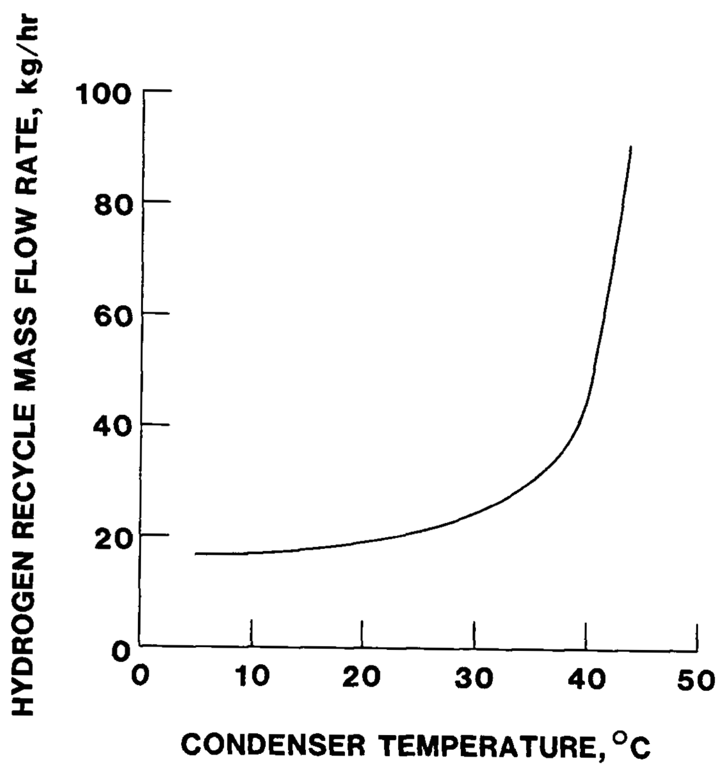

Figure 11. – Hydrogen recycle mass flow rate as a function of condenser operating temperature.

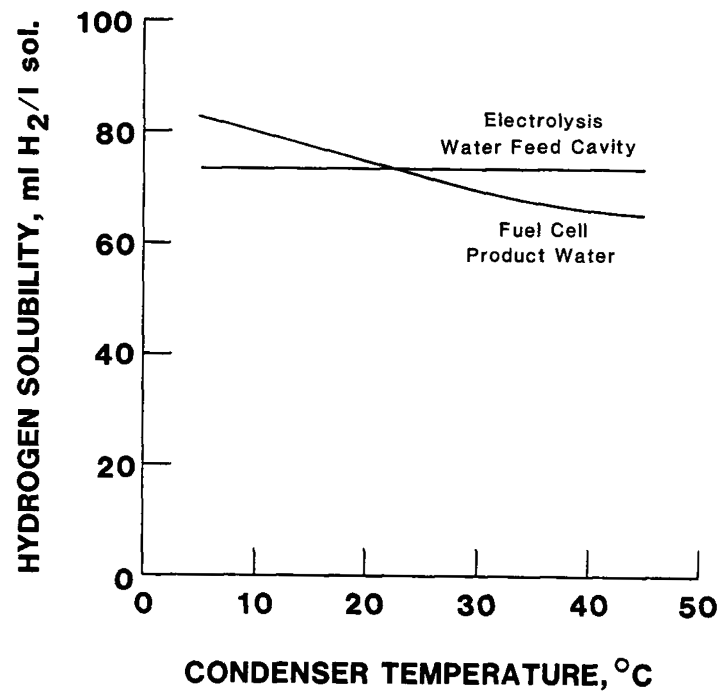

Figure 12. – Hydrogen solubility as a function of condenser operating temperature.

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15. Supplementary Notes

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16. Abstract

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