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ELECTROCHEMICAL LITHIUM POWER SYSTEMS FOR HYDROSPACE.(U)
JAN 74 H B URBACH, M C CERVI, D E ICENHOWER

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Report 27-415
Electrochemical Lithium Power Systems for Hydrospace

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Mark Cervi

David W. Taylor

NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

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ELECTROCHEMICAL LITHIUM POWER SYSTEMS FOR HYDROSPACE

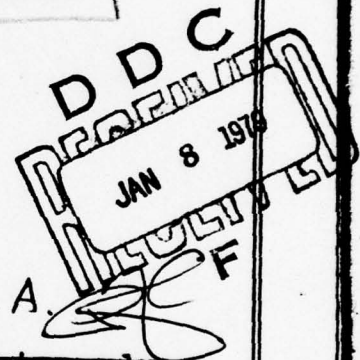
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H. B. Urbach, M. C. Cervi, and D. E. Icenhower

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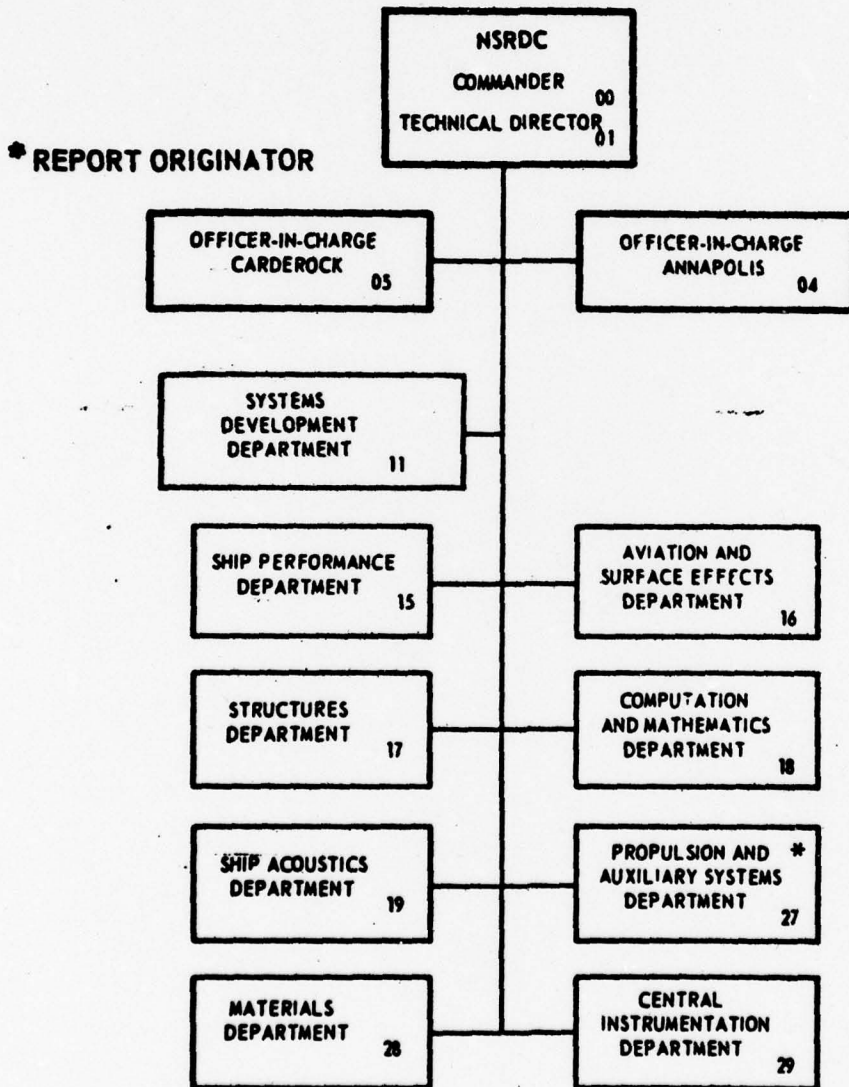
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ABSTRACT

Electrochemical cells consuming lithium and water were constructed and operated safely. The effect of lithium hydroxide electrolyte concentration temperature and cell configuration on the voltage, efficiency, and power output were studied.

Energies exceeding 1500 watt-hours per pound of lithium were obtained at powers of 160 watts per square foot, provided that the lithium hydroxide concentration and temperature were maintained at the optimized values. Coulombic efficiency increases as more power is drawn from the cell. Elevating temperatures above 25° C tended to lower efficiency by increasing the hydrogen self-discharge. However, higher temperature increases the amount of power available by increasing product solubility and decreasing activation losses. Studies of concentration effects indicate that maximum energy utilization of lithium can be achieved in cells employing between 3.50 and 3.70 molar lithium hydroxide concentration at temperatures between 15° and 25° C.

From the experimental data, a study was made of various multiple cell arrangements. Three configurations were studied, all having a square foot of single cell area and varying cell thickness. Because of requirements for neutral buoyancy, thin cells tend to have lower energy at higher power densities than thick cells. Assuming a conservative 1100 watt-hours per pound, calculations on a 10-kilowatt, fuel-cell stack employing 1-inch lithium plates indicate that about 12 watts per pound at 270 watt-hours per pound may be achieved. A system utilizing pure lithium is limited in its usefulness by large heat exchangers because of the requirement to maintain low temperature (approximately 15 to 25° C) for maximum efficiency. Calculations indicate that systems employing lithium alloyed with aluminum, may operate at temperatures of 40 to 50° C where energy- and power-weight ratios will be considerably higher.

ADMINISTRATIVE INFORMATION

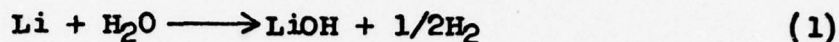
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INTRODUCTION

Electrochemical undersea energy sources utilizing lithium as a fuel have attracted great interest because of their large free-energy capacity of 3860 W-h/lb* of lithium. This energy derives from the reaction scheme shown in equation (1), consuming lithium and water in a 1:1 molecular ratio.



The aforementioned energy/weight ratio is based upon the weight of the lithium reactant only, since it is assumed that water is in virtually unlimited supply from the ocean environment.

Equation (1) indicates that the products of reaction consist of hydrogen as well as the hydroxide. The hydrogen would of course be available for additional release of energy in an environment capable of supplying oxygen as well as water in unlimited amounts. However, the addition of oxygen or another oxidant system to make possible the electrochemical utilization of the energy contained in hydrogen reduces substantially the overall energy/weight ratio from that achievable with lithium and ocean water alone.

The self discharge of hydrogen on lithium consumes the metal wastefully and depresses the coulombic and thermal efficiency. The self-discharge may be decreased by additional anodic loading to improve overall efficiency and to make the lithium cell a high-energy power source. The results of studies designed to yield such a power source and the preferred conditions of temperature, concentration, flow rate, and configuration which lead to an optimum efficiency in lithium cells are described herein.

*Abbreviations used in this text are from the GPO Style Manual, 1973, unless otherwise noted.

EXPERIMENTAL

APPARATUS

Fuel Cells

Two cells, a 6-W and a 25-W unit were constructed during the course of these experiments. The areas of the small and large cells were 5.4 and 24 in², respectively.

Figure 1 provides an exploded view of the 25-W cell which is similar in overall design to the 6-W unit. Neither unit was optimized for low weight or volume. The backup plates consisted of polysulfone sheets 3/4-inch thick. The contact screen consisting of lead-plated steel wire was imbedded in 1/8-inch thick lead. (It is anticipated that in devices of more sophisticated design, a 0.002-inch layer of lead on 0.018-inch magnesium will be used as a collector plate to minimize weight.) The lithium anodes which ranged from 1/8 to 1/4 inch were pressed onto the surface of the wire screen with a hydraulic press to make good electrical contact. The anode spacer was the same thickness as the lithium sample. Manifolding spaces were configured to obtain uniform flow in the cell so that consumption of the lithium would be uniform. The cathode, where hydrogen is generated electrochemically, consisted of platinum-catalyzed 0.030-inch nickel-felt metal. Separation between the anode and cathode was maintained by a thin rubber separator gasket, which varied from a few thousandths of an inch to 0.125 inch.

Fluid System

Figure 2 illustrates a schematic of one of the more convenient flow systems employed to study the lithium-water fuel cell. Electrolyte was pumped to the fuel cell at concentration levels ranging from 3.3 molar (M) to saturation at about 4.1 M. About 0.5 ft³/min/ft² was pumped to the cell at a pressure of approximately 2.5 lb/in². Fluid volume flows were monitored with a Fischer-Porter flowmeter.

The electrolyte was delivered and returned to the reservoir through heat exchangers. One precooling heat exchanger (not shown) was designed to produce massive cooling during temperature excursions resulting from excessive self-discharge. The temperature of the electrolyte reservoir, which contained up to 4 liters of fluid, was maintained by the postcooling heat exchanger.

The effluent line from the cell contained hydrogen produced at both anode and cathode. The electrolyte reservoir served as a phase separator. The hydrogen was permitted to escape from the system through a wet-test meter and bubble column (latter not shown) from which calculations of the lithium consumption rate were made. The measurements of the wet-test meter and bubble column often agreed within 5%.

Automatic Water Feed

An electrooptical shaft encoder ("Rotaswitch" made by Disc Instruments, Incorporated) delivered pulsed direct current (12 volts) to a solenoid-operated piston pump (Valcor Engineering Corporation) which injected between 0.1 and 1.0 ml of water with each pulse. The volume of water and the pulse frequency were sufficiently adjustable so that in a typical experiment the lithium hydroxide (LiOH) concentration changed less than 1% over a period of 150 minutes. The volume of water required for each quarter revolution of the wet-test meter (0.025 ft³ or 0.708 liter) varied with the LiOH concentration. Figure 3 shows the required theoretical feed rates of water for the range of gas evolution rates employed in the study. About 0.138 liter of water is required for each gram of lithium consumed.

A water-control system more suited to submerged conditions could utilize a conductivity cell to monitor the concentration of the LiOH (conductivity is a direct measure of concentration at fixed temperature). The conductivity could be fed into a comparator which controls the feed of water from the water reservoir to the electrolyte reservoir.

ELECTRONIC DATA MONITORING SYSTEM

A constant-current control was employed for most measurements of the performance of the lithium fuel cells. A Kordesch-Marko bridge was employed to measure ohmic losses in the fuel cells.

RESULTS AND DISCUSSION

COULOMBIC EFFICIENCY

As stated above, a significant feature of the electrochemical behavior of the alkali metals is the wasteful anodic evolution of hydrogen associated with the oxidation of these materials in the presence of water. This source of hydrogen is a measure of the coulombic inefficiency. On the other hand, total hydrogen evolution is proportional to the total lithium consumption rate at any time. The ratio of current delivered outside the cell to the total equivalent hydrogen current is the coulombic efficiency. (The equivalent hydrogen current is calculated from the faradaic conversion factor, i.e., 6.964 ml/min of hydrogen is equivalent to one ampere at standard temperature and pressure.) Thus, η_c , the coulombic efficiency is given by

$$\eta_c = \frac{6.964}{\dot{V}} \quad (2)$$

where I is the total observed current in amperes and \dot{V} is the hydrogen evolution volume rate in ml/min corrected to standard conditions.

Figure 4 shows the dependence of the coulombic efficiency calculated by means of equation (2) on the LiOH concentration. The higher the current density, the greater is the coulombic efficiency. (The crossover of the data for 3.32 and 3.49 M at 127 A/ft² is believed to be scatter.) Coulombic efficiency goes to zero at low current density because oxidation of the lithium by water, with hydrogen evolution, proceeds whether power is delivered or not. Slopes of the efficiency/current density curves increase with concentration. This result occurs because the lithium hydroxide product forms a protective layer over the lithium metal which diminishes the transport of water required for hydrogen formation. In more dilute solutions, the protective layer of LiOH is thinner because the solution of the hydroxide is faster. Moreover, there is of course more water available.

A surface layer of matter on the lithium, which may be LiOH (analyses by use of X-ray techniques proved to be inconclusive) with a coloration best described as "sky blue," was observed at temperatures above 40° C. (A bluish material has been reported to be a nitride of lithium.¹) This blue material imparted passivation to the lithium in aqueous methanol. It was present in thin layers probably less than 0.01 cm, relatively thin compared with the more bulky white layer of LiOH. A scratch of the thin passive blue material yielded an active area which produced hydrogen in copious amounts and the usual white hydroxide. The nature and thickness of these protective layers is believed to have profound influence over the anodic behavior of the lithium as suggested above.

Variability in the nature and in the thickness of the layers which may arise in part from changes in hydrodynamic flow, load, and temperature is the basis for considerable standard deviation in some of the data.

Figure 5 shows the effect on the coulombic efficiency of temperatures between 16° and 25° C. The maximum current density obtainable from the system is greatest at 25° C. The increased current density results from the slightly greater solubility of the LiOH, an increased rate of solution, and a smaller viscosity in the electrolyte. These factors tend to thin out the surface layer of hydroxide, reducing its contribution to the ohmic polarization loss and permitting higher current density. This thinning of the surface layer with temperature decreases the slopes of the plots shown in figure 5. Another temperature-related factor controlling the slopes is the activation energy of the process of hydrogen formation. The relative contributions of these two effects (thinning of the hydroxide layer and the activation energy) are not yet known.

The important conclusion to be found in figure 5 is that high temperature does not necessarily mean low coulombic efficiency. Approximately 65% coulombic efficiency is possible at both temperatures. Somewhat similar conclusions with respect to concentration may be drawn from figure 4. Thus, it is possible, by control of temperature and/or concentration, to obtain good coulombic efficiency over a wide range of loads.

¹Superscripts refer to similarly numbered entries in the Technical References at the end of the text.

VOLTAGE EFFICIENCY

The polarization curves permit immediate calculation of the voltage efficiency, η_v , from the expression

$$\eta_v = E/E_0, \quad (3)$$

where E_0 is the theoretical potential of the lithium-water system determined from its Gibbs free-energy, nominally 2.18 V (see discussion below.³)

The terminal potential and voltage efficiency exhibit complex response to increasing concentration of LiOH. According to figure 6, the potential appears to peak broadly between 3.5 and 3.7 M LiOH at current densities below 100 A/ft². Above 100 A/ft², the maximum terminal potential occurs around 3.5 M LiOH.

The falloff in performance is caused by factors which differ according to the concentration region. At low concentrations, e.g., 3.32 M, the observed lithium-hydrogen mixed potential at the anode is depressed by the hydrogen potential. This hydrogen potential becomes increasingly more capable of potential control when larger amounts of water are available (because the hydrogen electrode is then more reversible by the law of mass action). At high concentrations, i.e., above the optimum concentration between 3.5 and 3.7 M LiOH, the falloff arises from ohmic loss in the LiOH layer.

Rising temperature causes the polarization data to rotate in a counterclockwise manner around the open-circuit potential (see figure 7). This positive effect is diametrically opposite the very negative effect of temperature on the coulombic efficiency. A logical interpretation of these opposing effects of coulombic and voltage efficiency is best understood from the viewpoint of the power efficiency.

POWER EFFICIENCY

The power efficiency, the product of the coulombic and voltage efficiency, is the ratio of output power to the input rate of free-energy (Gibbs') delivery. The Gibbs free energy for the reaction of lithium and water is 96.1% of the enthalpy of reaction. Therefore, the thermal efficiency is obtained from the power efficiency by multiplying by the factor 0.961.

Figure 8 shows the coulombic, voltage and power efficiency plotted as a function of current density for a lithium fuel-cell system employing 3.89 M LiOH electrolyte at 25° F. The combined plots show graphically how the power efficiency depends on the product of the coulombic and voltage efficiency.

It is preferable to plot the power efficiency as a function of the power density for engineering purposes. Figure 9 shows such plots for power efficiencies at 16° C with varying concentrations. Low concentration depresses the slope of the power-density, power-efficiency plots. The dashed curve represents the envelope of data points for the various concentrations between 3.49 and 3.89 M LiOH. Energy/weight ratios based on the weight of lithium alone show values exceeding 1500 W-h/lb. Experiments at 16° C utilizing 3.72 M LiOH yielded energy/weight ratios exceeding 2300 W-h/lb. However, such a result was obtained in only two experiments for a period of 30 minutes and cannot be considered reproducible at this writing.

Figure 10 shows that increasing temperature rotates the slope of the power-efficiency, power-density plot in a clockwise direction about the origin. However, increasing temperature tends to increase the maximum achievable power density while depressing slightly the maximum achievable power efficiency.

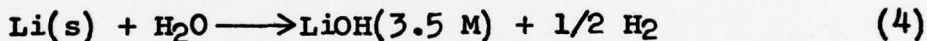
It may be concluded from figures 9 and 10 that the maximum power efficiency is closely associated with the maximum power density of the system at any given value of temperature and concentration. Nevertheless, in order to vary the load on a lithium fuel-cell system without significant depression of the power efficiency, it appears necessary only to vary the electrolyte concentration and/or temperature of the system. Either variation is feasible according to the experimental studies although there appeared to be some danger of uncontrollable thermal excursions in the latter case above 25° C. because of limited cooling capacity.

OHMIC FACTORS

The average dynamic resistance of the cell extracted from figure 6 is 5.5×10^{-3} ohms according to figure 11, which corresponds to a ohmic loss of 0.57 V at a 100 A/ft^2 current density. Such high values of ohmic potential loss have been experimentally verified at 100 A/ft^2 levels by use of a Kordesch-Marko bridge. Based on an interelectrode space of 0.10 inch and 3 ohms-cm for the resistivity of the electrolyte, a resistance of only 8.2×10^{-4} ohms is calculated. It must be concluded that ohmic loss factors in the electrolyte alone cannot explain observed dynamic resistances which probably arise from the hydroxide surface layers on the lithium as suggested above. The increase in dynamic cell resistance below 3.5 M LiOH is probably caused not by ohmic factors but by electrochemical kinetic factors peculiar to mixed potential systems.

COMPUTATION OF THE THEORETICAL FREE ENERGY

The potential and free energy of reaction for lithium and water have been listed by Latimer.³ The process described by equation (1) would be modified for optimization so that the concentration of LiOH is roughly 3.5 M. The statement of the reaction would also be modified thus:



The activity of the water in the solution can be assumed unity. Since the activity-coefficient of 3.5 M LiOH is 0.49, the thermodynamic activity³ of the LiOH is 1.622, corresponding to a pH value of 14.21. In normal acid solution the potential is 3.045 V (for pH of zero) and 2.217 V at pH of 14. The correction for 14.20 pH units is -0.8407 V yielding 2.204 V and 50.84 kcal for the working potential and Gibbs free energy per gram mole. These correspond to 3.86×10^3 W-h/lb of lithium.

Studies of the lithium cell at the Center have revealed open circuit potentials ranging from 2.32 to 2.36 V under open circuit conditions for periods up to 15 minutes. These high potentials could be an artifact arising from the presence of oxygen. If these potentials are not an artifact, then it is possible to conclude that Latimer's listing³ for the standard potential of the lithium, lithium-ion couple (pH = 0) is low by 0.116 V. (Latimer states that discrepancies exist between

published experimental and theoretical values which are 2.957 and 3.045 V, respectively. See references in Latimer's bibliography.) Thus the standard potentials are perhaps closer to 3.16 V (pH = 0) and 2.33 V (pH = 14). The potentials must be regarded as preliminary pending further confirmational experiments. In this study values employed for the potential and the energy/weight ratio were 2.18 V and 3860 W-h/lb, respectively.

COMPARISONS

Halberstadt has described results obtained by L. S. Rowley, L. B. Anderson et al, of Lockheed Missiles and Space Company (LMSC).⁴

The obvious conclusions to be drawn from a comparison of the data⁴ are that results at the Center are in fair agreement with results of the Lockheed studies. The Center reports high power efficiencies which were achieved by operating at low temperatures at the expense of power density. Conversely, the Lockheed studies show that higher power densities may be achieved at higher temperature with some sacrifice of power efficiency.

CONCEPTUAL DESIGN STUDY OF A 10-KW, 200-KWH POWER SYSTEM

During the course of the experimental investigation several studies of the overall performance of a lithium-fueled electrochemical power system were made to obtain an estimate of the position of lithium cells on an overall power-energy map. Several configurations were analytically examined and found to exhibit a good energy/weight ratio. The power-weight ratio may be varied widely as required. The system described herein was based on the use of data obtained at 25° C where the maximum observed energy/weight ratio is only about 1100 W-h/lb at 130 W/ft². Higher performance values could of course be chosen, but they were precluded by the requirement that the lowest temperature of water for cooling was only 15 1/2° C (60° F).

The calculated overall mass and energy flows are shown in figure 2. Total lithium charge for the system is 220.7 lb in 1-inch plates of 1 square foot. Since the electrolyte concentration (see figure 7) is 3.9 M, 359.4 lb/h of water is added. This water feed corresponds to 39.49 lb of water per pound of lithium or 6.93 grams of water per 0.1 ft³ of hydrogen gas evolved according to figure 3. Vented from the system are 1.31 lb/h of hydrogen and 349.0 lb/h of solution. Because of the low density of lithium, 18.2 lbs/h of solution are accumulated in the stacks as the lithium reacts.

At 10 kW of power output 24.7 kW (84,300 Btu/h) is dissipated in the heat exchanger, and 0.4 kW is assumed to be delivered to the pump and auxiliaries.

The design is based on a total of 80 cells placed in two stacks of 40. The intercell spacers and cell framing contain all manifolding and parts for the delivery of electrolyte and egress of electrolyte and gas. Dry and wet (with sea water containing lithium hydroxide in correct concentration flowing through the manifolding and filling the interelectrode spaces) weights and volumes calculated from these designs are listed in table 1. The end-plate contributions to weight and volume have been distributed evenly; i.e., 2.5% per cell.

TABLE 1
WEIGHT AND VOLUME BREAKDOWNS OF
THE SINGLE CELL* AND STACK

| State | Weight lb | | Volume ft ³ | |
|--------------|--------------|-------|---------------------------|--------|
| | Per Cell* | Stack | Per Cell* | Stack |
| Dry unfueled | 2.703 | 216.2 | 0.02274 | 1.819 |
| Dry fueled | 5.461 | 436.9 | 0.1061 | 8.468 |
| Wet unfueled | 9.553 | 764.2 | 0.1268 | 10.145 |
| Wet fueled | 6.800 | 544.0 | 0.1268 | 10.145 |

*Including end plate contributions of 2.5% per cell.

The lithium charge per cell in 1-inch plates is 2.758 lb, or 40.5% of the total weight of 6.80 lb per element. Only 95% of the lithium is assumed to be available.

The pump size was determined from experimental data which indicated a pressure drop of approximately 2 lb/in² across the pump from pressure losses in the cell and heat exchangers. Throughputs of 0.00937 ft³/ft²-s in 80 cells amount to a pumping dissipation of 0.293 kW. Assuming pump and motor efficiencies of 0.8 and 0.9, respectively, 0.406 kW of pumping power is required, which represents 3.9% of the gross output power of 10.4 kW.

Table 2 shows the breakdown of weight and volume for the system. The initial and final weights for the stacks differ because of the replacement of low density by higher density electrolyte. Requirements for neutral buoyancy may be met by retention of hydrogen gas in plastic bags or in a buoyancy control tank. However, the table shows 178.5 lb of plastic foam (33 lb/ft³) designed to bring about neutral buoyancy at maximum weight.

TABLE 2 - GROSS COMPONENT WEIGHTS AND VOLUMES FOR A 10-KW SYSTEM

| Item | Volume | Weight |
|---|------------------------|---|
| Cell stacks | 10.145 ft ³ | 544.0 ⁽¹⁾ / 764.3 lbs ⁽²⁾ |
| Pump motor | 0.051 | 7 |
| Pump | 0.029 | 5 |
| Wet inventory | 0.175 | 12 |
| controls | 0.156 | 10 |
| Heat exchanger | 0.091 | 51 |
| Subtotal | 10.65 | 629.0 ⁽¹⁾ / 849.3 ⁽²⁾ |
| Foam | 5.41 | 178.5 |
| Total | 13.42 ft ³ | 807.5 / 1028.1b |
| Power | | 10. kW |
| Energy | | 230. kW-h |
| Power/weight ratio | 11.8 ⁽³⁾ | 9.7 ⁽⁴⁾ wt-h/lb |
| Energy/weight ratio | 271 ⁽³⁾ | 224 ⁽⁴⁾ wt-h/lb |
| (1) Initial weight (2) Final weight (3) Based on final weight without foam (4) Based on final weight with foam | | |

Weights of pumps and motors have been conservatively set at 15 and 10 lb/hp. The weight of the heat exchanger has been sized in accordance with the weights of the heat exchangers employed in other preliminary design studies.⁵

Overall power- and energy/weight ratios (assuming neutral buoyancy may be achieved by bagging evolved gas) are 11.8 W/lb and 271 W-h/lb, respectively (see figure 12). By simply cutting the thickness of the cells (and increasing the number of cells inversely) from 1-inch lithium slabs to 0.5-inch slabs (and 160 cells), the power/weight ratio may be increased to 17.2 W/lb with, however, a loss in the energy/weight ratio.

Based on the conceptual design calculations above, power/weight ratio and energy/weight ratios of 25 W/lb at 270 W-h/lb, respectively, may be anticipated in systems of similar design, provided cooling water is available to permit operation of the cells at temperatures of 16° to 17° C. The power density may be doubled approximately if both sides of the lithium plate are employed (with some small loss in the energy/weight ratio).

CONCLUSIONS AND RECOMMENDATIONS

Single lithium-water fuel cells have been successfully operated over a range of conditions and power varying from 5 to 30 W. Operating temperatures, examined over a range between 10° and 70° C, yielded maximum performance (cell power efficiency) at temperature values below 30° C. The concentration of the electrolyte was varied between 3.3 and 4.0 M and yielded optimum energy/weight ratios around 3.7 M.

Coulombic efficiency is depressed with increasing temperature and enhanced with increasing concentration. On the other hand, output potentials increase with temperature. The potential exhibits (over the useful current density range) a performance maximum as the concentration of electrolyte is varied. At 16° C, the potential maximum is observed in a concentration range between 3.5 and 3.7 M.

The power efficiency increases with concentration at any given temperature. For a given concentration the power efficiency is enhanced with decreasing temperature.

An energy/weight ratio of 2300 W-h/lb (based on lithium) at a power density of 145 W/ft² has been intermittently observed for about 30 minutes at 16° C. Energy/weight ratios in the neighborhood of 1400 to 1500 W-h/lb (based on lithium) at 150 W/ft² appear routinely obtainable on demand in the single cells studied.

A conceptual design analysis of a lithium fuel cell system of 80 cells capable of delivering 10 kW at 230 kW-h shows that power- and energy/weight ratios of the order of 12 W/lb and 270 W-h/lb, respectively, are obtainable. A system of similar design employing 160 lithium cells (with half the lithium anode thickness (would have power- and energy/weight ratios of the order of 17 W/lb at 200 W-h/lb, respectively. Using a two sided configuration in the lithium cells, the power density may be approximately doubled. Energies such as 200 W-h/lb are significant in comparison with the capabilities of many battery systems.

Severe limitations associated with the lithium-water system arise from the unusually low cooling temperature requirements. A lesser limitation arises from the low density of lithium which changes the overall buoyancy of the system as it is consumed. In a previous report⁶ it was shown that mixtures of lithium and aluminum are capable of delivering increased amounts of both power and energy at higher temperatures. It is recommended that additional experimental work be performed to test the feasibility of lithium-aluminum alloy fuel cells operating at temperatures of the order of 40 or 50° C. Such operation would substantially increase the power density without change in the energy/weight ratio.

It is noted that the manual recharging of lithium-based fuel-cell systems would be highly disadvantageous in some underwater operations. Attention should therefore be directed to the evolution of lithium-based systems which may be automatically recharged or to systems in which safe, simple, and rapid manual recharge may be effected underwater. Naturally, with systems requiring complicated nonelectrical recharge, some limitations to their application will exist, particularly in environments which are climatically extreme.

The reader is reminded that the results and conclusions reported herein, while intended for submersible applications, were obtained under a few inches of water at pressures which can best be described as atmospheric.

The rapid exploitation of lithium-based fuel-cell systems in deep-submergence operations requires that these devices be subjected to the extremes of cyclic pressure that may be anticipated in such applications.

Finally, the reader is reminded that the reported results are based on single cells and do not reflect the complications arising from a common electrolyte when cells are stacked to achieve higher potentials.

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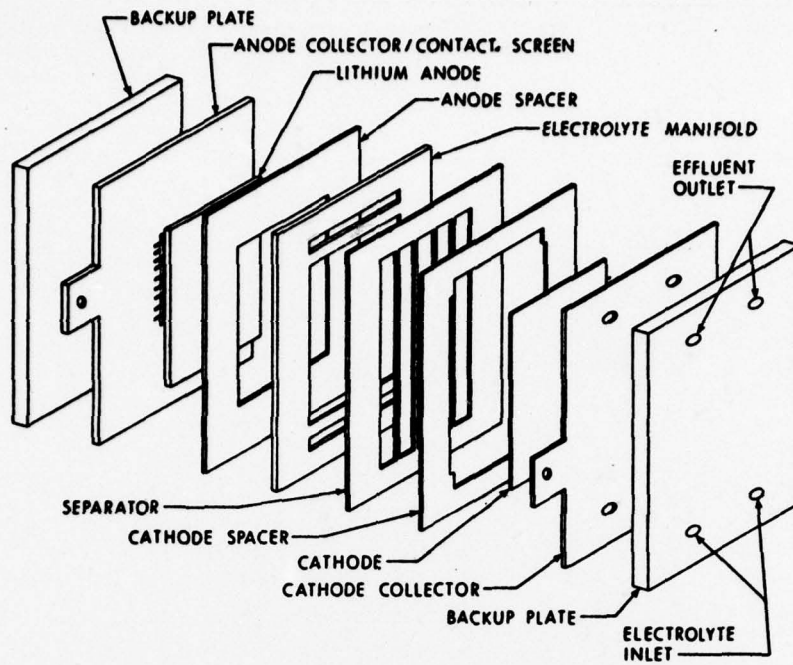


Figure 1 - General Schematic of the Experimental Lithium-Water Fuel Cell

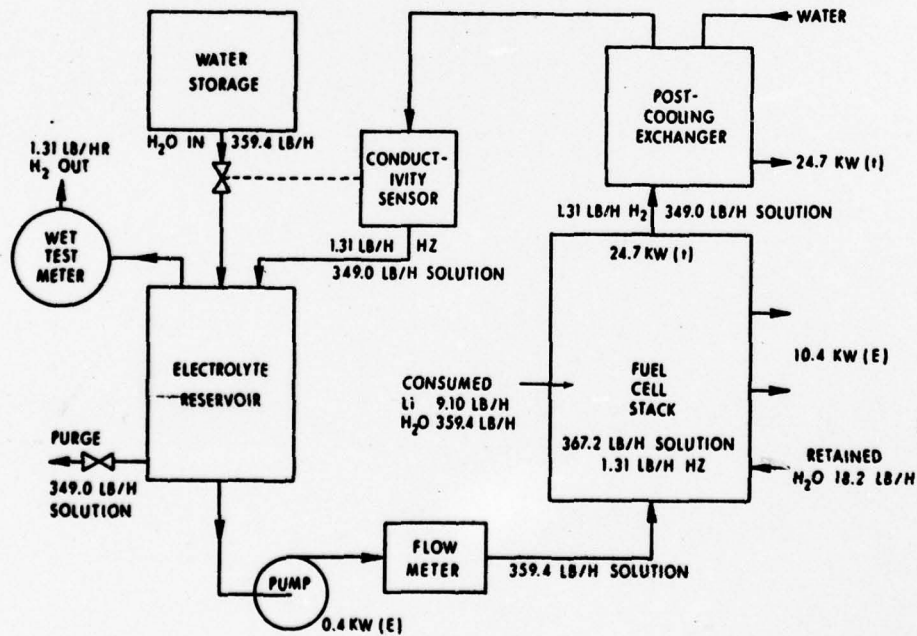


Figure 2
Flow Diagram of One Breadboard System

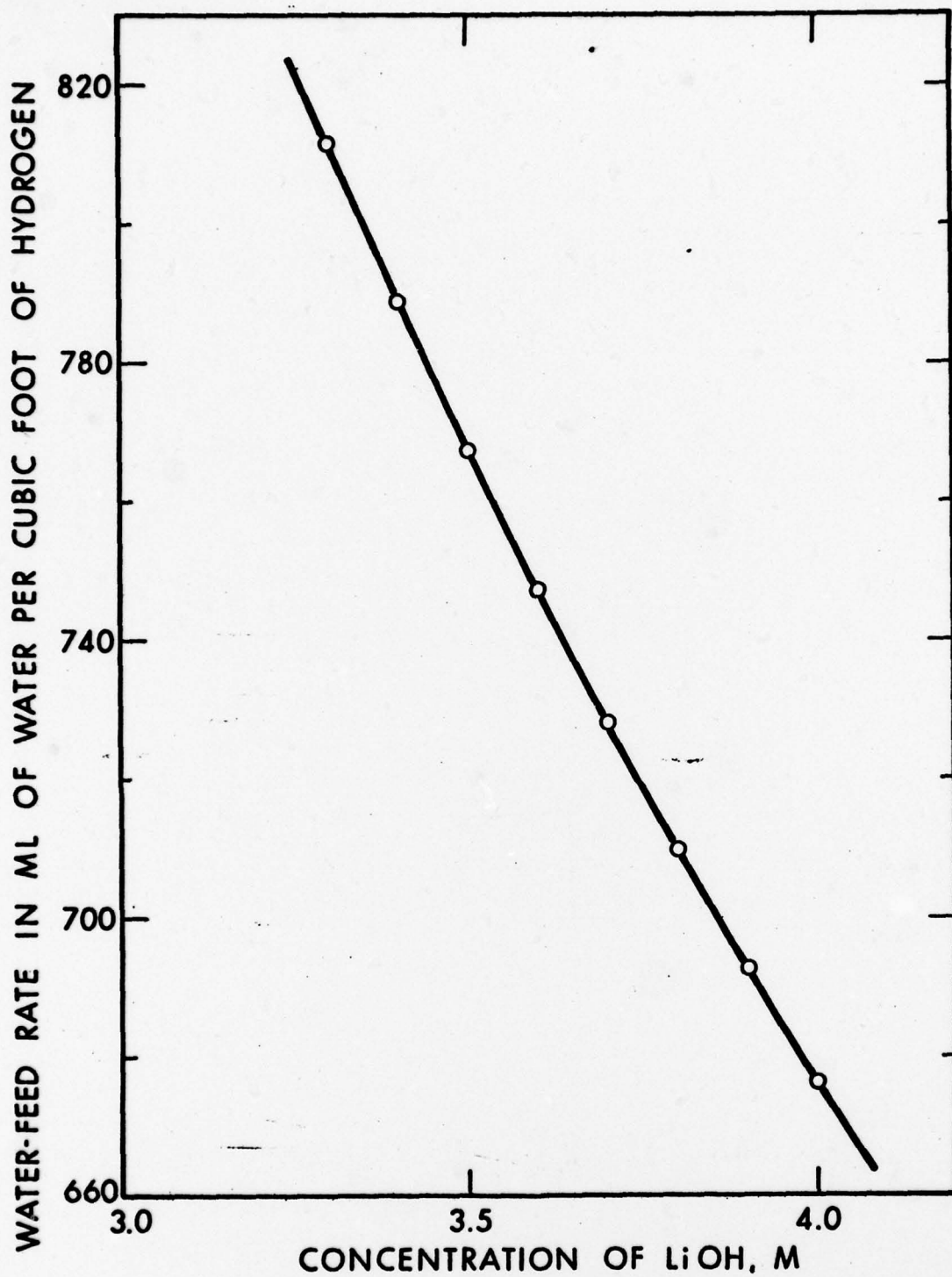


Figure 3
Water-Feed Rate Requirements as a
Function of Lithium Hydroxide Concentration

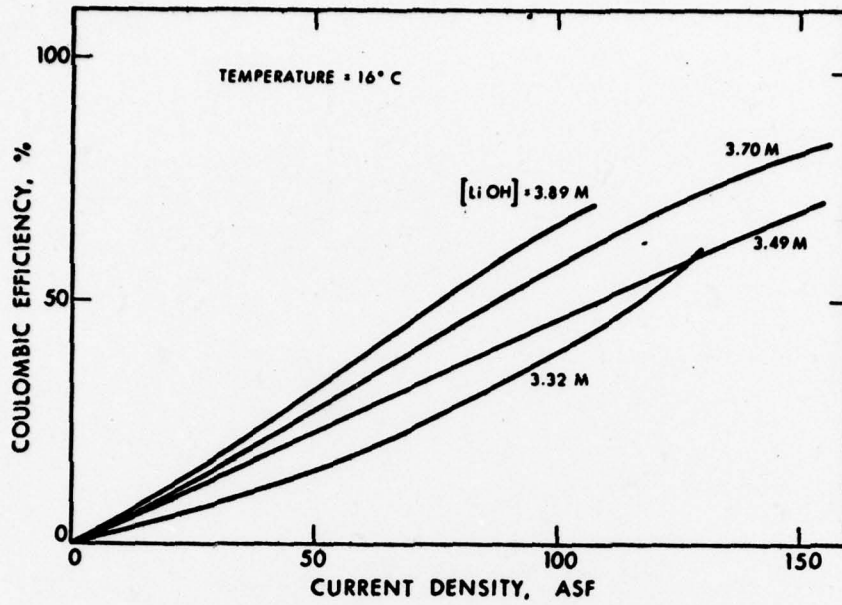


Figure 4 - Dependence of the Coulombic Efficiency on Electrolyte Concentration

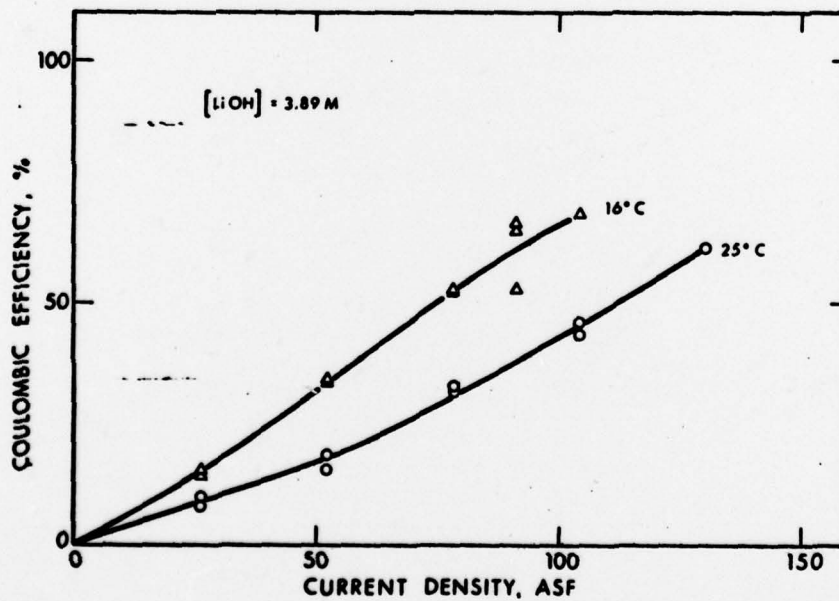


Figure 5 - Effect of Temperature on the Coulombic Efficiency

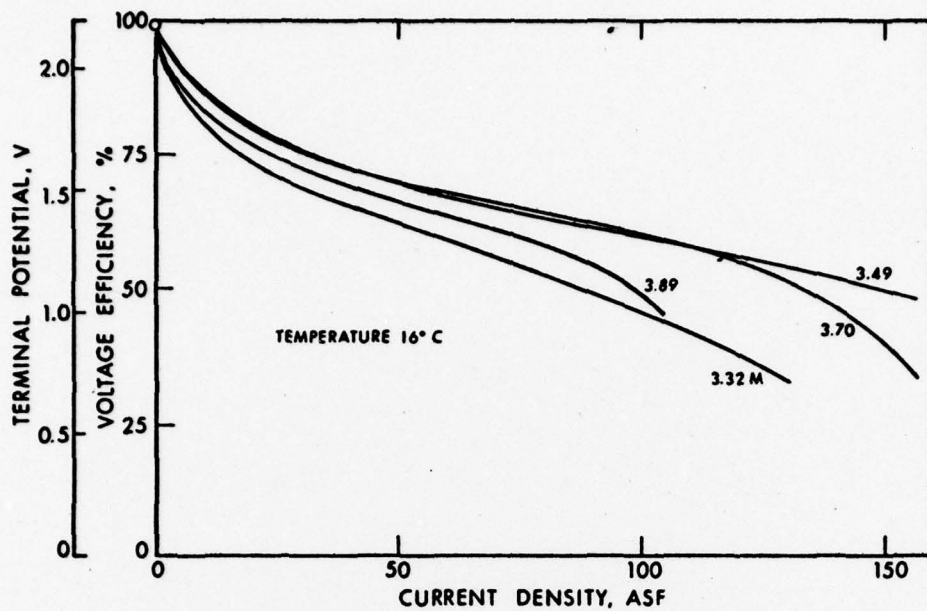


Figure 6 .
Concentration Behavior of the Polarization

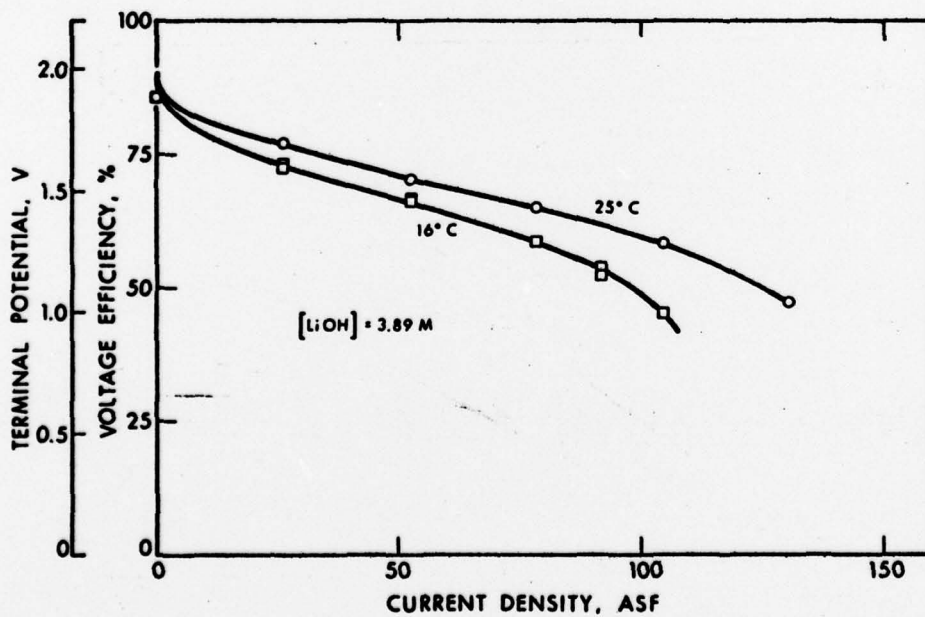


Figure 7
Influence of Temperature on the Polarization

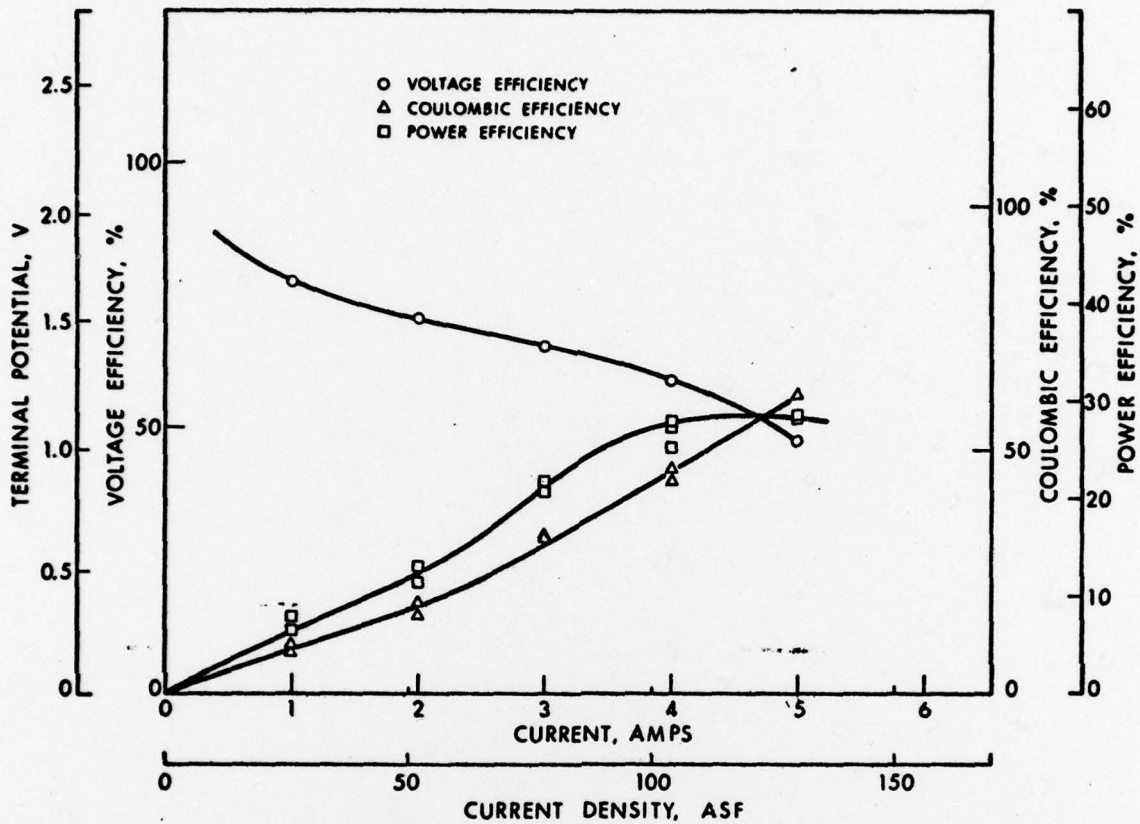


Figure 8
Efficiency Relationships as a Function
of Current Density

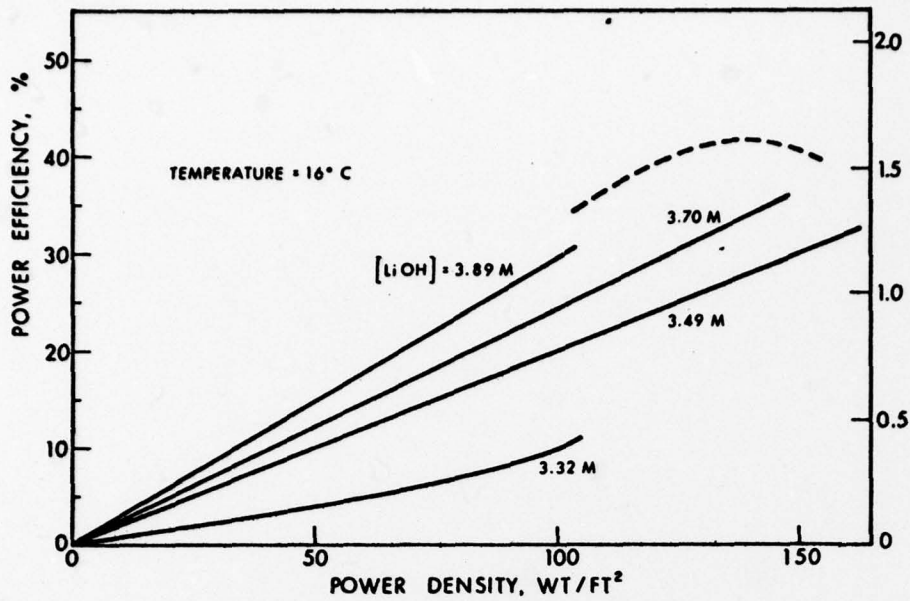


Figure 9 - Response of the Power Efficiency, Power-Density Relation to Concentration

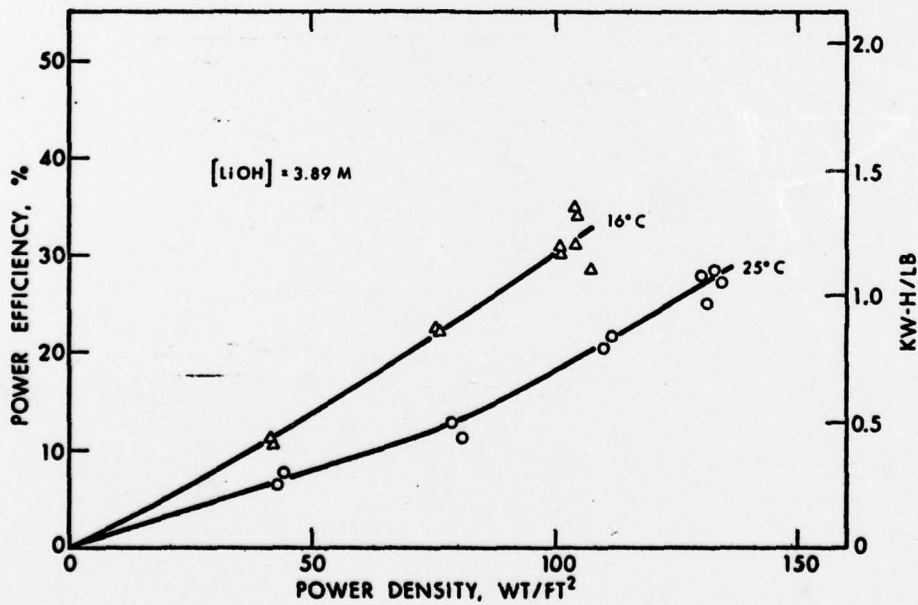


Figure 10 - Effect of Temperature on the Power-Efficiency, Power-Density Relation

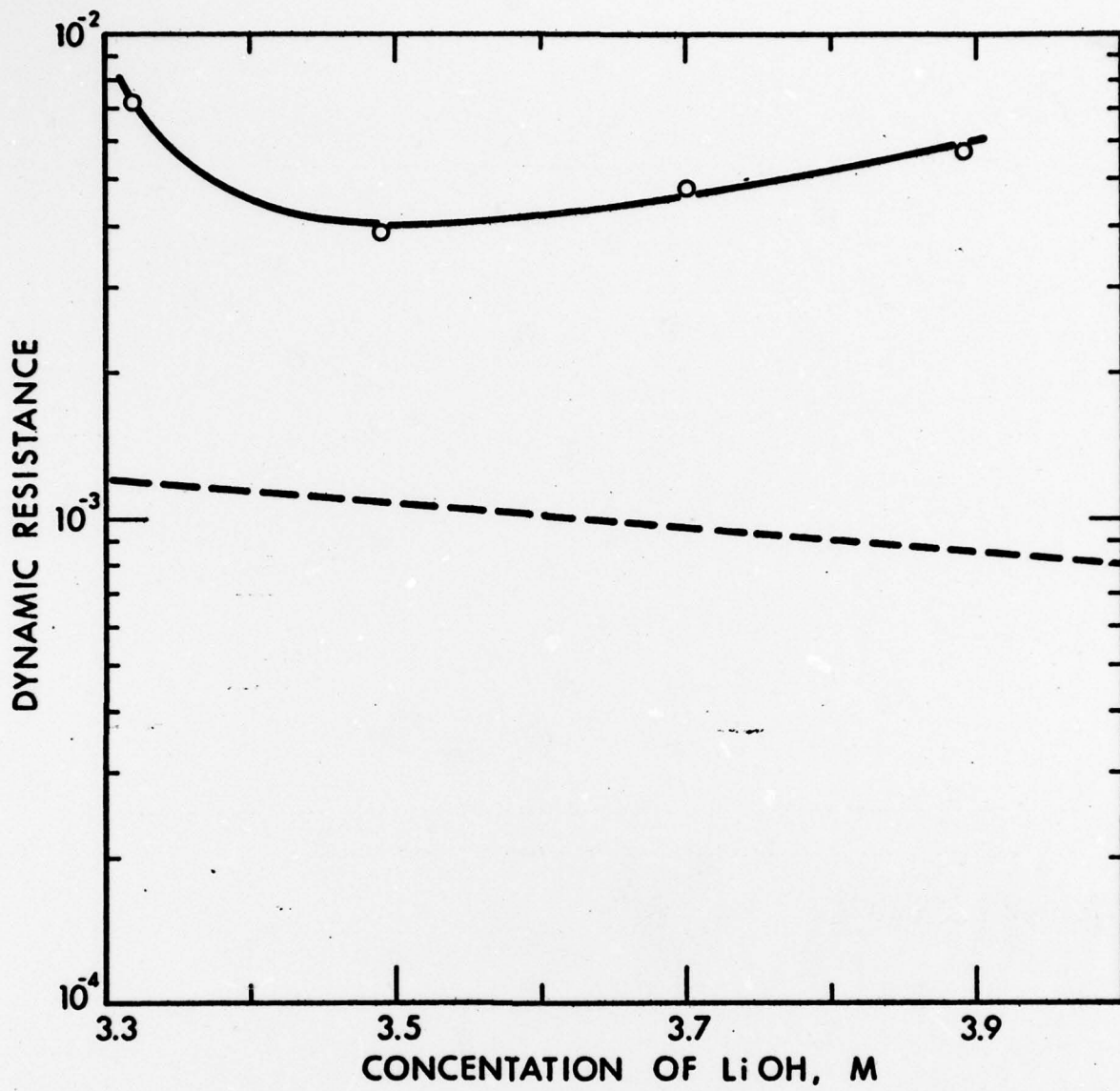


Figure 11 - Effect of Concentration on the Dynamic Resistance of a Lithium Cell (Area = FT²)

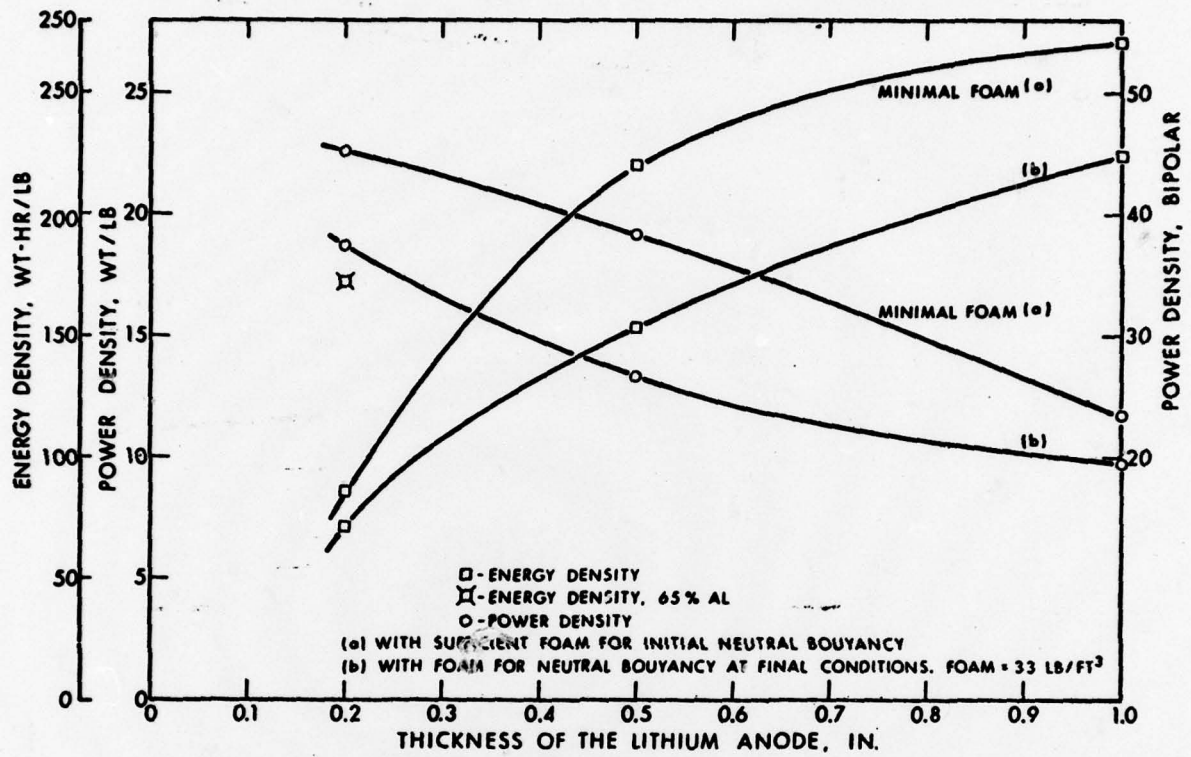


Figure 12
Comparative Power- and Energy-Weight Ratios

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