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## ASSESSMENT OF THIN FILM BATTERIES BASED ON POLYMER ELECTROLYTES

### III. Specific Energy vs Specific Power

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### ABSTRACT

The feasibility of solid state polymer electrolyte batteries for applications such as the electric vehicle depends on the variation in the performance levels of the specific energy and specific power. In this paper efforts have been centered mainly on rechargeable lithium batteries with electrolyte complexes formed between polyethylene oxide and lithium salts having an ionic conductivity of  $10^{-4} (\Omega\text{cm})^{-1}$  and  $\text{V}_6\text{O}_{13}$  insertion cathodes. Prismatic unit cells of variable cathode thicknesses have been modeled and calculated results indicate that high specific energies ( $\sim 200$  Wh/kg) and high specific powers ( $\sim 700$  W/kg) are possible for this battery system utilizing metallic current collectors. Considerably higher values result for low density metallized plastic current collectors.

### 1.0 INTRODUCTION

Considerable efforts are underway at several laboratories around the world to develop an all-solid state rechargeable high energy density polymer electrolyte battery based on lithium anodes

and insertion cathodes[1 - 5]. The most popular polymer electrolyte studied has been based on complexes formed between polyethylene oxide and lithium salts.

One of the major shortcomings of this type of battery system is the low ionic conductivity of the solid polymer electrolyte at ambient temperatures ( $10^{-9}$  -  $10^{-8}$  ( $\Omega\text{cm}$ ) $^{-1}$ ). Recently, however, a number of laboratories have described modified polymer electrolytes with high ionic conductivity at room temperature ( $10^{-5}$  -  $10^{-3}$  ( $\Omega\text{cm}$ ) $^{-1}$ )[6 - 9]. This has led to the industrial development of this type of battery system in a number of countries. Current efforts are focused on developing batteries for a number of applications, including electric vehicles[1,10]. Performance data indicate that if polymer electrolyte batteries can be successfully scaled up, they should provide up to five times the energy density of a lead-acid car battery. Experimental studies on small prototypes (1-6 cm<sup>2</sup> area) show that such batteries now provide an energy capacity of up to 200 Wh/kg. However, translating the promise of laboratory cells into a fully scaled-up commercial battery, for example in electric vehicle propulsion, requires solving formidable technological problems. Two of the most critical are manufacturing and networking. A number of scale-up issues are presently being confronted by several groups[1,3,11,12]. Although the manufacturability of these thin film materials may pose little problems, since they can be processed by conventional automated techniques, the ability to link a number of cells together with appropriate series/parallel connections in either unipolar or bipolar modules and to cycle them without individual cell failure poses a major challenge.

In order to scale-up any battery system, it is first important to model the theoretical performance behavior. A basic disadvantage of a polymer electrolyte battery is that the weight and volume of essential, but non-reactive, components, such as current collectors, bipolar connectors, insulators etc., significantly reduce the achievable energy and power densities[2,12]. These contributions must be minimised by the choice of appropriate materials and fabrication technologies. Several materials can be used to increase the energy and power density of this system. They include, low density metals (e.g. Al), metallized plastic current collectors and electronically conductive polymers. In previous articles[12,13] the first two choices were used to model the energy density and pulse power behavior of a lithium polymer electrolyte battery.

A common representation of a battery's performance is made through a Ragone plot that describes the cell's specific power (W/kg) versus its delivered specific energy (Wh/kg). Most of the

cell performance studies on polymer electrolyte batteries have been based from an energy density point of view. Little has been reported on the power density aspect of this system or the variation in the energy and power density. The only group that has reported practical data describing the energy and power relationship is IREQ[1,10,14]. They have investigated the behavior of two types of lithium polymer electrolyte batteries, one operating at elevated temperatures (80° - 140°C) and the other operating at 25°C and below. The cell configurations were designed for electric vehicle propulsion and the generated Ragone plot data were compared to the conventional lead-acid and nickel-cadmium batteries.

Although this kind of plot is a useful tool to describe a battery's performance behavior, it is important to realize that there is a correlation between the cell performance and loading capacity of the cathode where the full cell reaction take place. Cells with higher capacities (thicker cathodes) will yield higher energies at low power with the added benefit of a relative reduction in weight in the active components. On the other hand, cells with low capacities (thinner cathodes) will yield higher powers and hence higher currents with correspondingly lower energies. Hence the configuration of a particular battery system depends on the type of application.

This paper describes the theoretical variation of the specific energy and power of a lithium polymer electrolyte battery. Only the unit cell case is considered with two types of current collectors and different loadings of the positive electrode.

## 2.0 DESIGN CONCEPT

The unit cell design of the lithium polymer electrolyte battery utilizing an insertion type cathode has already been described[12]. In this paper the same variable parameters were considered. The treatment used to generate Ragone plots was that described by McLarnon et al.[15] whereby only the ohmic contribution was considered. In such cases the cell's voltage (V) and power densities (P) are given respectively by,

$$V = V_1 - IR \quad (1)$$

and

$$P = IV = I(V_1 - IR) \quad (2)$$

The cell capacity was assumed to decrease linearly with increasing current and the maximum cell current corresponded to a pseudo-ohmic potential drop equal to  $V_1$ . The cell's specific energy ( $E$ ) is then given by,

$$E = VQ = (V_1 - IR)Q_0(1 - (IR/V_1)) \quad (3)$$

Combining (2) and (3) gives[15],

$$P = V_1^2/R[(E/V_1Q_0)^{1/2} - (E/V_1Q_0)] \quad (4)$$

By taking into account the necessary weights of the active and inactive components, similar to those used in earlier studies[12], one obtains a relationship that describes the variation in the cell's specific energy with specific power. The discharge rates considered in this paper were between C/100 and 5C.

### 3.0 RESULTS AND DISCUSSION

Figure 1 shows the theoretically calculated Ragone plots for prismatic unit cells having a cell area of  $400 \text{ cm}^2$  utilizing Ni current collectors and variable cathode thickness. The cathodes thicknesses were 1, 10 and  $100 \text{ }\mu\text{m}$ . The plots indicate that high energy capacities are dominated by the thicker cathode cells and high power capacities by the thinner cathode cells. However, there is a limiting value in the cathode thickness whereby the power density does not increase any further with decreasing cathode thickness and in fact tends to decrease. This is unexpected at first sight, but a careful analysis of equation (4) indicates the equation to be inexact for cathode thicknesses less than  $10 \text{ }\mu\text{m}$ . In addition, at very high rates of discharge, the calculation corresponds to the

ohmic contribution being greater than  $V_1$  (although this is not possible in practice) and this results in a peak in the curve instead of a plateau. None the less, equation (4) gives a good representation for moderate thickness cells. For the 100  $\mu\text{m}$  thick cathode, the variation in the specific energies with powers are large. Cell specific energies greater than 200 Wh/kg are calculated at rates lower than C/5, but the specific power corresponds to less than 200 W/kg. At high rates of discharge, (2C), specific powers of about 800 W/kg are possible but with severe penalties in the specific energy (  $\sim 50$  Wh/kg ). As the cathode thickness decreases, the weights of the inactive components tends to become more significant as far as the energy density values are concerned and decreases correspondingly. However, since the electrolyte thickness decreases proportionately [12], also, the power density increases. For thinner cathodes, (  $\sim 10 \mu\text{m}$  ), the energy density varies little with discharge rates, but the specific power increases rapidly with higher rates of discharge. Power densities greater than 3 kW/kg can be obtained at the 5C rate with specific energy values corresponding to 36 Wh/kg.

Figure 2 shows Ragone plots for prismatic unit cells with metallized plastic current collectors, 400  $\text{cm}^2$  cell area and again variable cathode thickness. The same kind of behavior is seen in this case as with the Ni current collector cell (Figure 1), in that a limiting value is reached in the cathode thickness whereby the power density values actually decreases. A striking feature of this plot is that it shows the effect of low density inactive components such as metallized plastic current collectors on the energy and power capabilities. The calculated energy density for the 100  $\mu\text{m}$  thick cathode corresponds to greater than 400 Wh/kg at discharge rates lower than C/5. This is more than double the value for the Ni current collector cell calculated for the same rate. At higher rates of discharge, (2C), maximum specific power of 1.4 kW/kg are calculated. For the 10  $\mu\text{m}$  thick cathode, the specific energy varies little with discharge rates as observed with the Ni current collector type cells and is about 200 Wh/kg. However the specific power increases rapidly with increasing discharge rates, and values as high as 18 kW/kg are calculated at the 5C rate.

Figure 3 shows a comparison of the Ragone plots for the Ni and metallized plastic current collector cells of area 400  $\text{cm}^2$  and 10 and 100  $\mu\text{m}$  thick cathodes. The figure clearly demonstrates that, as expected, by far the best energy is obtained for the thicker cathode and conversely the best power results for the thinner cathode. In addition, the use of low density

current collectors such as metallized plastics has a strong impact in increasing the specific energies and specific powers of the system.

Figure 4 shows Ragone plots for prismatic polymer electrolyte unit cells with Ni current collectors and 100  $\mu\text{m}$  thick cathodes as a function of cell areas. A limiting value is reached with increasing cell areas. Optimum specific powers of 400 - 700 W/kg and optimum specific energies of 150 - 200 Wh/kg are calculated at moderate rates (C - 2C) of discharge for cell areas ranging between 100 and 400  $\text{cm}^2$ .

Figure 5 shows the corresponding Ragone plots for 100  $\mu\text{m}$  thick cathode cells utilizing metallized plastic current collectors. Again a limiting value is observed as the cell area increases, which means that increasing the cell area excessively does not necessarily mean a large increase in the specific energy or specific power. Optimum cell areas corresponds to about 100 to 400  $\text{cm}^2$  giving optimum specific energies of about 300 Wh/kg (2C rate) and optimum specific powers of about 1 kW/kg.

Figure 6 compares the calculated values from this work for 100  $\mu\text{m}$  thick cathode cells utilizing Ni current collectors and cell areas ranging between 25  $\text{cm}^2$  and 400  $\text{cm}^2$ , with practical values for a nickel-cadmium, lead-acid and a moderately scaled-up polymer electrolyte battery. The data for the polymer electrolyte battery is derived from IREQ[1] and is for a 10 Wh demo cell having an electrolyte thickness of 50  $\mu\text{m}$  and operating at 100°C. It is assumed that the conductivity of the electrolyte at this temperature is the same as that assumed in this work ( $10^{-4}(\Omega\text{cm})^{-1}$ ). The electrolyte thickness for a 100  $\mu\text{m}$  thick cathode in this case corresponds to 20  $\mu\text{m}$ [12]. This should result in a much higher specific power than that obtained by IREQ's practical demo cell. Figure 6 shows this to be the case. However, our calculated power values only include ohmic losses and thus are higher. Although the comparison is not exact, it never the less demonstrates the operating range of this system. Utilization of metallized plastic current collectors significantly increases the energy and power capabilities. In addition, for larger applications such as electric vehicle propulsion, the use of bipolar electrode configurations should further increase the specific energy and power.

The above results indicate that in order to scale-up this type of system, it is important to know the theoretical performance limits for various configurations of cells. The modeling work

demonstrates that even after allowing for sufficient polarization losses and assuming less than 100% cathode utilization, the lithium polymer electrolyte battery appears to have several fold advantage over the present day nickel-cadmium or lead-acid batteries. High specific energy and high specific power polymer electrolyte batteries can be successfully built only by optimization of the variable parameters. The main goal of IREQ's technology is for the electric vehicle propulsion. This requires high specific sustained powers of over 100 W/kg for 30 seconds or more for example in hill climbing, and high specific energies greater than 50 W/kg for steady driving. It appears that the lithium polymer electrolyte battery appears feasible for this application.

#### 4.0 CONCLUSIONS

The lithium solid state rechargeable polymeric electrolyte battery appears to be a highly promising electrochemical power source. High energy and power ratings have been calculated for practical unit cells. Considerably higher values of specific energies and powers are predicted for the bipolar design.

#### ACKNOWLEDGEMENT

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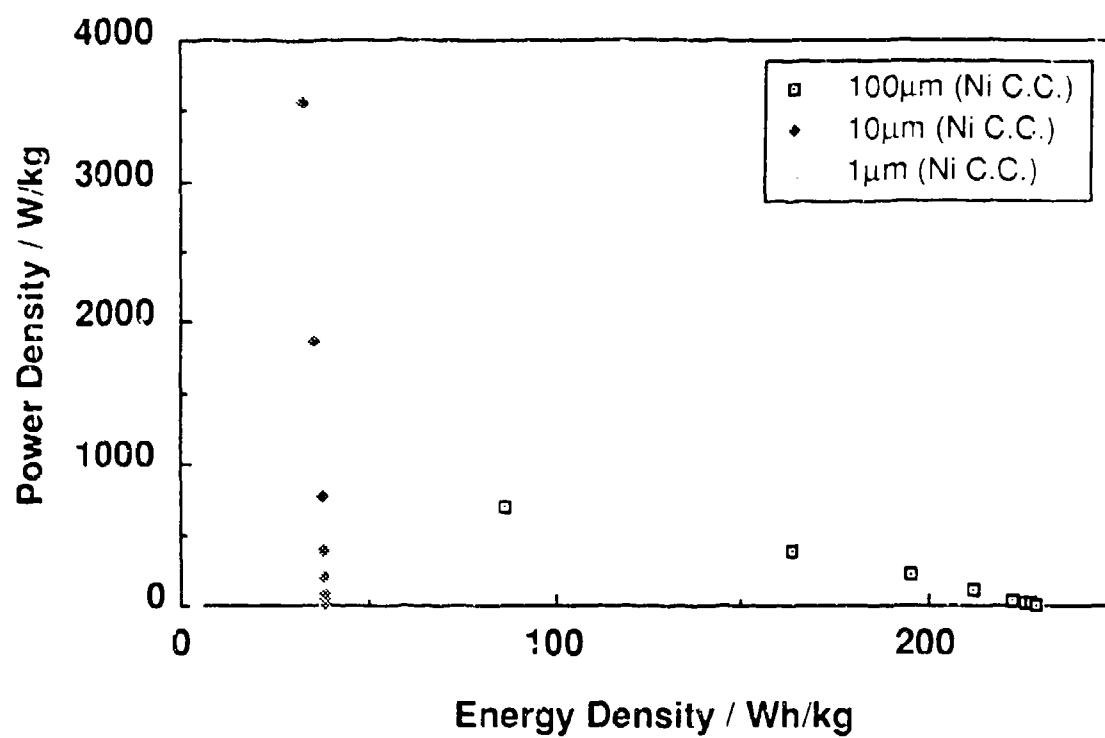


Figure 1. Ragone plots for prismatic unit cells with Ni current collector, 400 cm<sup>2</sup> cell area and variable cathode thickness.

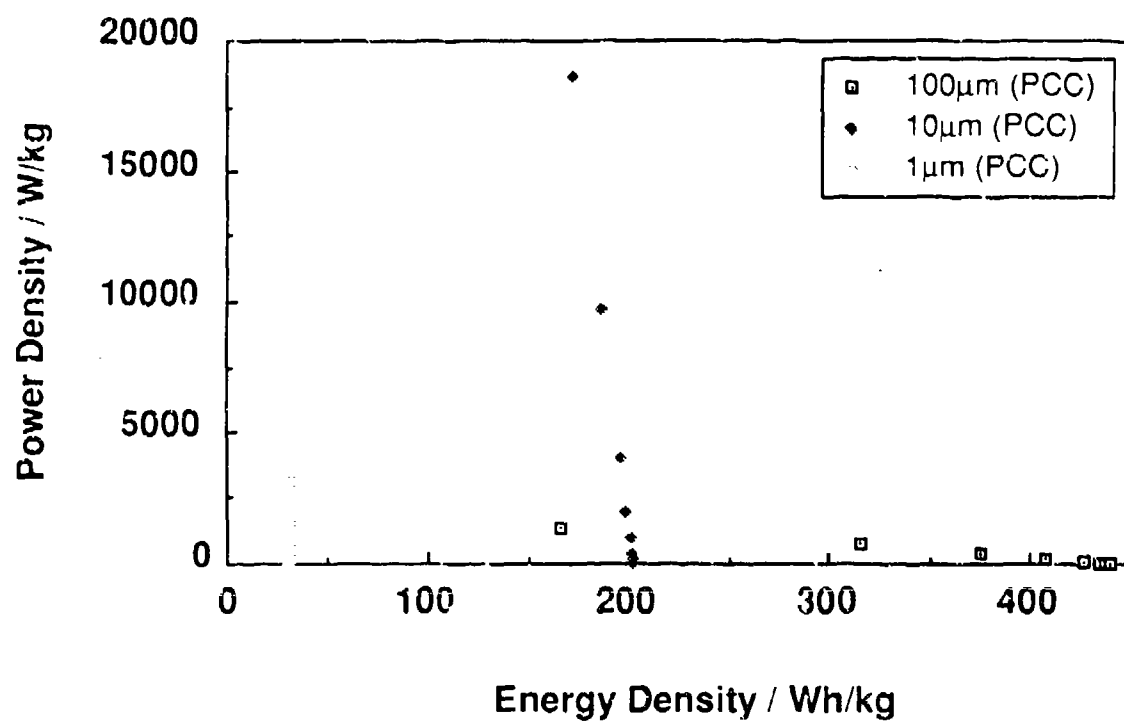


Figure 2. Ragone plots for prismatic unit cells with metallized plastic current collector, 400 cm<sup>2</sup> cell area and variable cathode thickness.

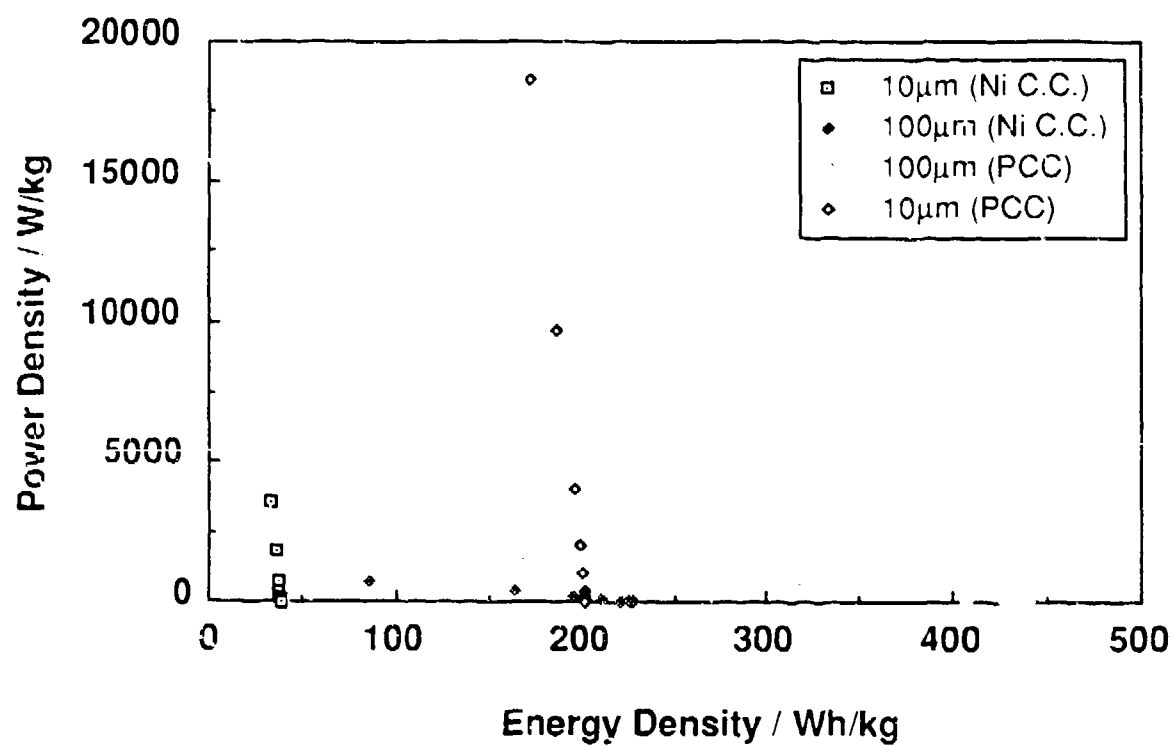


Figure 3. Ragone plots for prismatic unit cells, 400 cm<sup>2</sup> cell area and 10 and 100 μm thick cathodes.

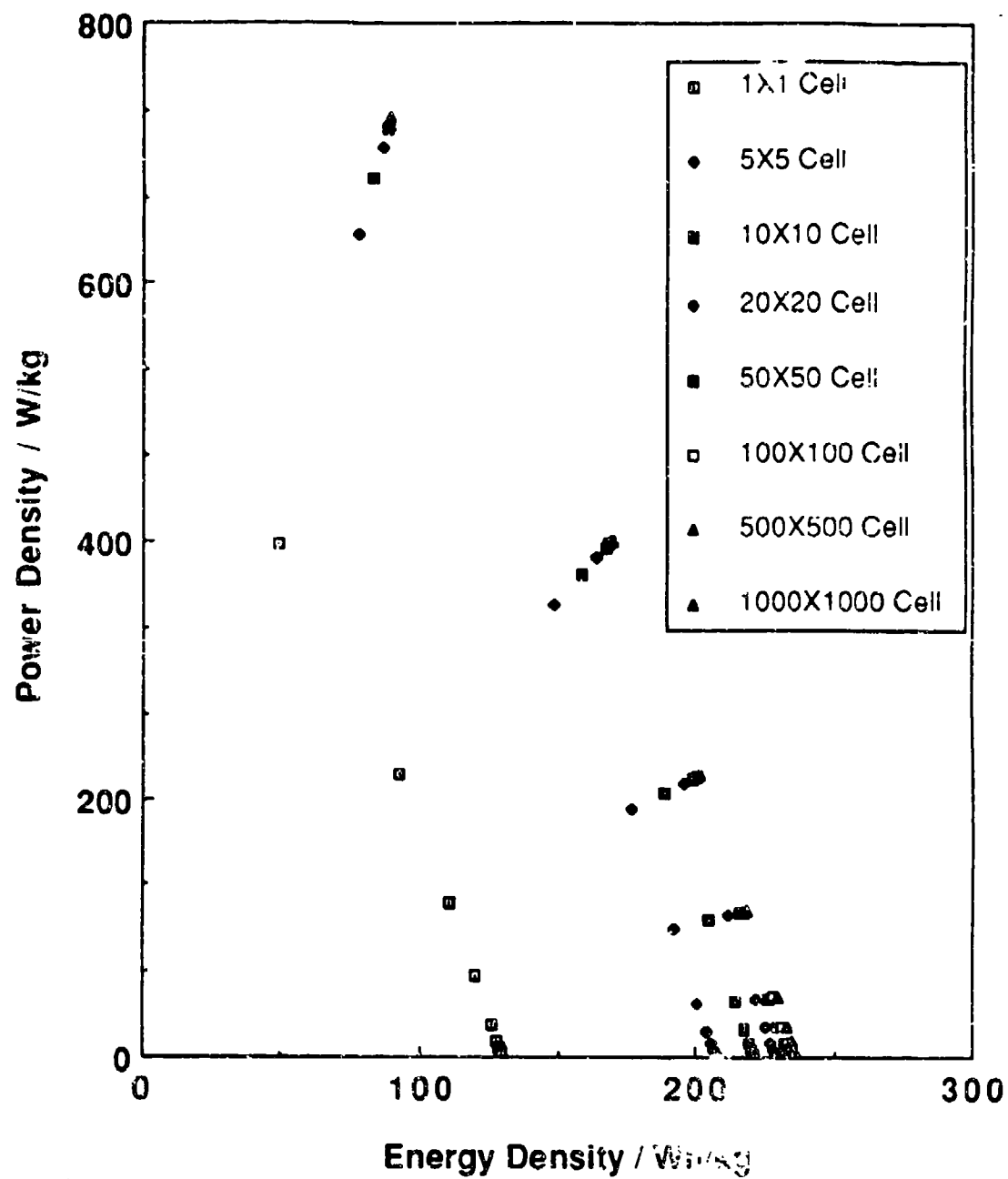


Figure 4. Ragone plots for prismatic unit cells with Ni current collector, and 100  $\mu\text{m}$  thick cathode.

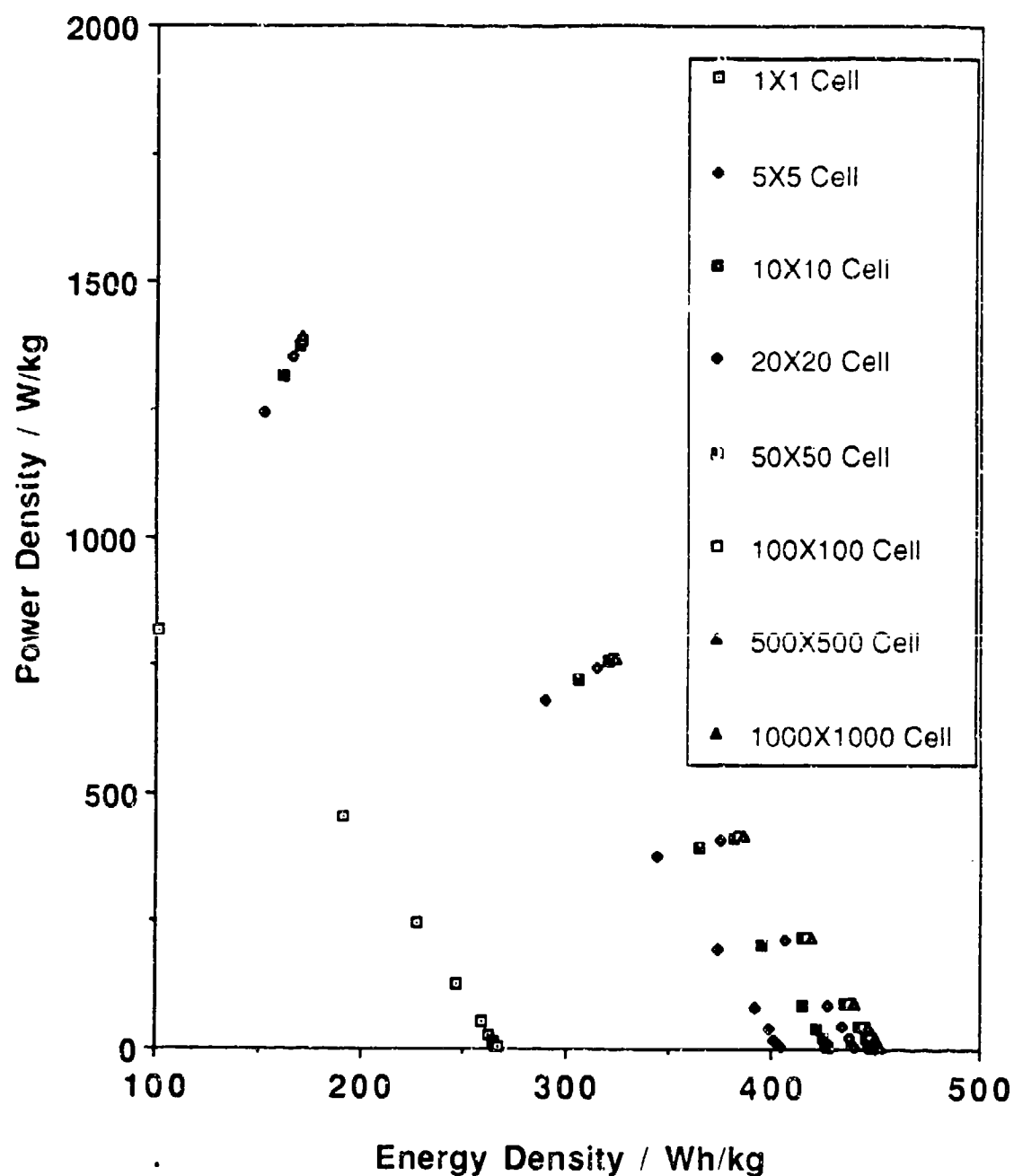


Figure 5. Ragone plots for prismatic unit cells with metallized plastic current collector and 100  $\mu\text{m}$  thick cathode.

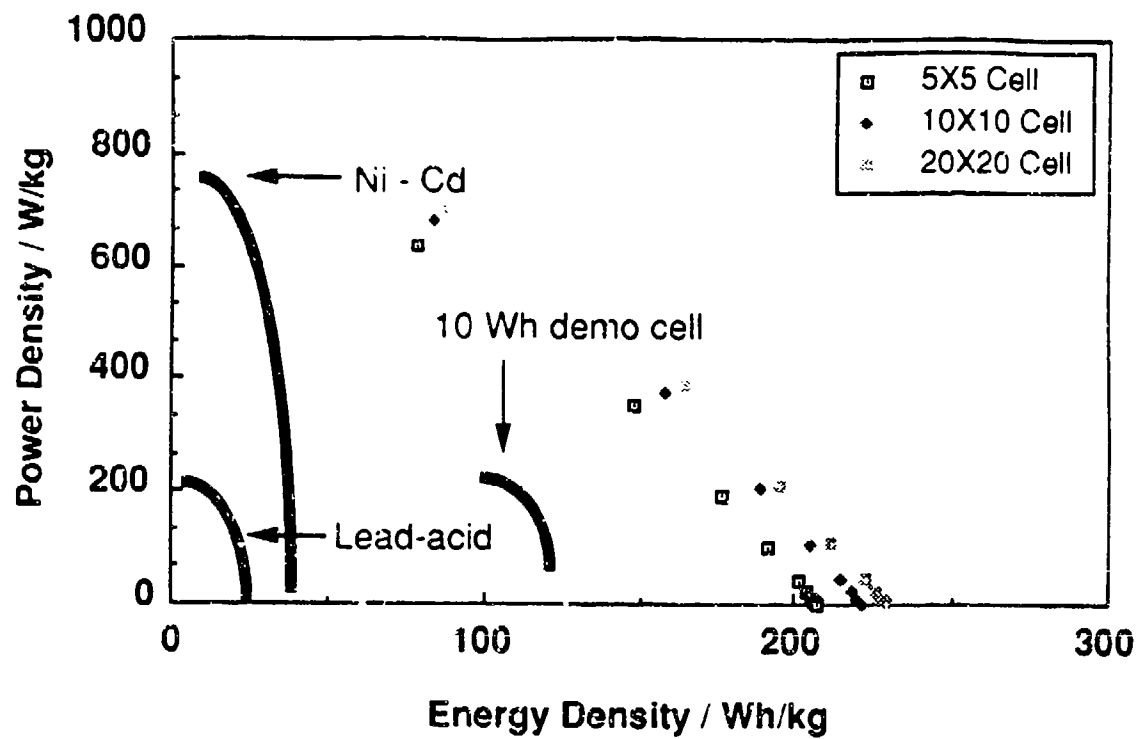


Figure 6. Ragone plots for different battery systems.