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Design and Modeling of Cylindrical and Flat-Wound Lithium-Ion Cells for the PNGV Application*

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DISCLAIMER

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ABSTRACT

In this study, 10-Ah cylindrical and flat-wound cells were designed and studied for use in batteries for the Partnership for a New Generation of Vehicles (PNGV). A low-cost current collection system was devised that results in a low resistance. Heat rejection from flat cells is much better than that from cylindrical cells and is an important safety factor. Very compact, powerful batteries of about 1.5 kW/L can be designed with wound lithium-ion cells.

INTRODUCTION

Batteries for the Partnership for a New Generation of Vehicles (PNGV) program require a very high power-to-energy ratio, approximately 10, to achieve the high power, light weight, and low cost required by the application. The requirements can be met with lithium-ion cells by use of thin laminar cell designs that are wound in many layers around a central core, which results in a high ratio of electrode area to weight. A large cell capacity (10 Ah) was selected for this study to investigate the feasibility of designing a 40-kW battery with a single string of 100 series-connected cells or a smaller battery of fewer cells, which would be less expensive.

Spreadsheet models were developed for both cylindrical and flat-wound cells to facilitate the study of the effects of variables upon the projected cell performance.

CELL DESIGN

The cylindrical and flat-wound cells have several features in common. The electrodes, separators, and electrolyte materials are those described in the experimental studies on 32-cm^2 cells by K. Amine et al. (1). To meet the requirement of high specific power, the electrodes are very thin and are coated on both sides of the current collector foils, providing a large surface area. To attempt to meet the stringent cost goals for PNGV ($300 per 25-40 kW battery), the positive electrode in this design is $LiNi_{0.8}Co_{0.2}O_2$, which is less costly than the more established $LiCoO_2$ material. The electrolyte-free positive electrode is 8% carbon, 8% binder (PVDF), and the balance active material. The negative electrode is 91.5% graphite and 8.5% binder (PVDF). Celgard^{TM} separators and $LiPF_6$/ethylene carbonate/dimethyl carbonate (EC/DMC = 1:1) electrolyte (35.7 vol% in the positive electrode and 34.9 vol% in the negative electrode) are employed. The layered structure of the cell consists of bicell electrodes and separators as described in Table I. The delivered capacity density is that measured after 10 cycles of break-in on 32-cm^2 laboratory cells and is equivalent to 160 mAh/g of active positive material. The cell area is the same for all cells (6760 cm^2) and is sufficient for 10 Ah of capacity at a 1-h discharge rate. The area-specific impedance (ASI) is approximately that reported by Amine et al. (1) for 32-cm^2 cells.

Table I. Layer Structures for 10-Ah Wound Cells

Delivered Capacity Density (1-h rate), mAh/cm^2	1.48
Negative-to-Positive Ratio (delivered capacity)	1.23
Thickness of Cell Layers, μm	
Cathode	
Electrode Material Coating (single layer)	44
Central Aluminum Current Collector	20
Anode	
Electrode Material Coating (single layer)	47
Central Copper Current Collector	12
Separators	37
Total Bicell Layered Structure	288
Cell Area, cm^2	6760

To accommodate the large surface area, the cells are formed by wrapping the layered cell structure around a polymer core, which is a 6-mm cylinder for the cylindrical cells and a 1-mm plate for the flat cells. The cells are shown in Fig. 1. Preliminary calculations showed that the use of only several small tabs to collect current from the current-collector foils of a 10-Ah cell would result in much of the cell resistance being in the current collection system. To achieve the high power required by the PNGV application, current has to be efficiently collected from each wrap of current-collector foil. Preliminary calculations showed that the current collection system would be a major contributor to the total cell impedance if only a few current collection tabs were used. We have developed a low-cost method for attaching the current collector foils to the terminals that result in low resistance. This effect can be seen by comparing the calculated ASI of the entire cell (Table II) with that of the layered structure, which was 25 ohm-cm^2. Both terminals are located at the top of the cell to facilitate connections to adjacent cells. It is proposed that the aluminum tops of the cells be fastened to a deep drawn container by means of crimping or welding.

In this study, we developed separate spreadsheet models for cylindrical and flat-wound cells to study the effects of cell variables upon the cell performance. The thicknesses of the electrode coatings (Table I) were determined from their compositions and the material densities. For the cylindrical cells, the width of the winding structure (which determines the height of the cell) was fixed, and the diameter of the winding was adjusted by automatic iteration until the capacity of the cell matched the input value of 10 Ah. A winding compaction of 95.5% of full density was projected. In a similar manner, the dimensions of the flat cells were determined by fixing the width of the winding structure and the number of winding layers (288-μm thickness, Table I) and adjusting the width of the cell until the capacity matched the input value of 10 Ah.

The impedance of the cell was calculated from the measured ASI of 32-cm^2 cells (Ref. 1 and Table I) and the resistance calculated for the current collection system, which is a function of the cell dimensions. The cell volume was calculated from the overall cell dimensions. The weight of the cell was calculated from the volumes and densities of the individual parts of the cell. Because of the stringent requirements for energy efficiency and the narrow operating voltage range for the PNGV battery, the maximum power was calculated for a voltage of 85% of open circuit voltage at 50% depth-of-discharge (DOD).

To assist in evaluating cooling requirements for the cells, the dimensions of a 100-cell battery were projected as part of the modeling study. The cylindrical cells are assembled in a triangular array to form a 20-cell module with six cells in the center row and seven cells in the side rows. Spacers maintain a 3-mm gap between cells to provide a flow area for coolant. The flat cells are also formed into twenty-cell modules with spacers providing a 1-mm wide flow space between the cells. The battery was projected to consist of five modules (100 cells total in series connection) with sufficient space for connections and flow passages and 8-mm-thick exterior insulated walls.

Heat transfer calculations were made to determine the temperature rise at the center of the cells over the coolant inlet temperature. A high rate of heat generation of 5 W per cell was assumed. That heat rate exceeds the amount that will be generated by cells in a PNGV battery in normal service (2). However, the malfunctioning of a cell might generate heat at an even higher rate, so a conservative standard must be set for the allowable temperature rise for both the cell and the coolant. Two coolants were considered: air and a dielectric fluid.

The spreadsheets were designed with the input and calculated parameters listed in a single column at the left of the spreadsheet. All of the numerical values for a cell under study are then listed in a single column. Most of the input values are near the top of the spreadsheet to accommodate new entries, and the calculated parameters, which use the same formula in every column, draw only from values within that column. Thus, several cells can be easily studied at once. This facilitates graphing the effect of one input variable upon a calculated parameter, such as the effect of cell diameter upon cell power. The printouts for the computer programs for the cylindrical and flat cell battery designs are 12 pages for each program, not including graphs and drawings. However, the calculations are completed in a few seconds after a change in input variables, facilitating rapid study of many variables.

RESULTS

Calculated results from the battery design modeling programs showed that the cell configuration affects the current collector resistance and, thus, the cell power. For a fixed cell capacity, 10 Ah for this study, decreasing the height of the cylindrical cell increases the diameter. The decease in height reduces the resistance in the current collection system, resulting in lower total ASI and higher power (Fig. 2). Cooling is more difficult as the cell is increased in diameter, so two cells of different diameters were selected (Fig. 2) for comparing the results with those for flat cells. For flat cells, the cell width was varied at a fixed cell height by adjusting the number of windings. The variation in cell width by this means has very little effect on the cell ASI and power, but wide, thin cells have higher weight and, thus, lower specific power than narrow cells (Fig. 3). The performance of three selected cells is compared in Table II. All of the cells have excellent electrical performance because of the effective current-collection systems. The cylindrical cells have lower weight, but also slightly lower power than the flat cell.

Table II. Performance for Cylindrical and Flat-Wound Cells

	Cylindrical A	Cylindrical B	Flat
Capacity, Ah	10	10	10
Height, mm	110	170	110
Diameter or Thickness, mm	40	32	13
Width, mm	-	-	125
Current Shoes per Electrode	1	1	1
Area Specific Impedance, ohm-cm^2	27.1	28.7	26.5
Weight, g	298	308	352
Volume, cm^3	138	136	169
Open Circuit Voltage at 50% DOD, V	3.7	3.7	3.7
Power, W	435	412	445
Specific Energy, Wh/kg	118	114	100

A comparison of the dimensions of batteries assembled with the selected cylindrical and flat cells is shown in Table III. The height of the battery assembled from "B" cylindrical cells may be slightly greater than desired, but overall, the dimensions and the total volumes of less than 30 liters are excellent for all of the batteries, which provide more than 40 kW of power.

Table III. Battery Dimensions for Cylindrical and Flat-Wound Cells

	Cylindrical A	Cylindrical B	Flat
Cell Height, mm	110	170	110
Cell Separation for Coolant, mm	3	3	1
Number of Modules	5	5	5
Number of Cells	100	100	100
Battery Wall Thickness, mm	8	8	8
Battery Dimensions, mm			
Height	149	209	149
Length	622	511	659
Width	324	267	296
Volume, L	30.0	28.5	29.0
Power, kW	43.4	41.1	44.3
Battery Power Density, kW/L	1.45	1.44	1.53

Cooling with a dielectric fluid is much more effective than air cooling for both cylindrical and flat cells (Figs. 4 and 5 and Table IV). The air film next to the cell container is a major fraction of the resistance to heat transfer from the center of the cell. The cylindrical cells are difficult to cool with both coolants, especially for cell diameters greater than 32 mm. The selected flat cell, which is 125-mm wide and 13-mm thick, is attractive for its cooling performance. For that cell, the rise in temperature above that of the adjacent liquid coolant is only 1.4°C. This provides an adequate degree of safety if an internal cell short circuit results in a heat-generation rate many times higher than the projected normal cooling rate of 5 W per cell.

Table IV. Heat Transfer from Cylindrical and Flat-Wound Cells

	Cylindrical A	Cylindrical B	Flat
Cell Height, mm	110	170	110
Diameter or Thickness, mm	40	32	13
Container Area for Heat Transfer, cm^2	138	170	248
Heat Loss Rate, W	5	5	5
Liquid Coolant Inlet Temperature, °C	20	20	20
Coolant Temperature Rise, °C	4	4	4
Cell Center Temperature Rise (above adjacent coolant), °C	9.6	6.2	1.4

CONCLUSIONS

A means of attaching the current collector foils to the cell terminals has been developed that results in a low resistance. Positioning both terminals at the top of the cell is easily achieved and is advantageous for connection into a battery. Heat rejection from flat cells is much better than that from cylindrical cells and is an important safety factor.

Very compact, powerful batteries of about 1.5 kW/L can be designed with wound lithium-ion cells.

ACKNOWLEDGMENT

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[1] K. Amine, J. Liu, A. N. Jansen, A. Newman, D. Simon, and G. L. Henriksen, in *Intercalation Compounds for Battery Materials*, G.-A. Nazri, M. Thackeray, and T. Ohzuka, Editors, PV 99-24, p. 389, Electrochemical Society Proceedings Series, Pennington, NJ (2000).

[2] P. A. Nelson, G. L. Henriksen, and K. Amine, in *Power Sources for the New Millennium*, PV 2022, Electrochemical Society Proceedings Series, Pennington, NJ (2001).

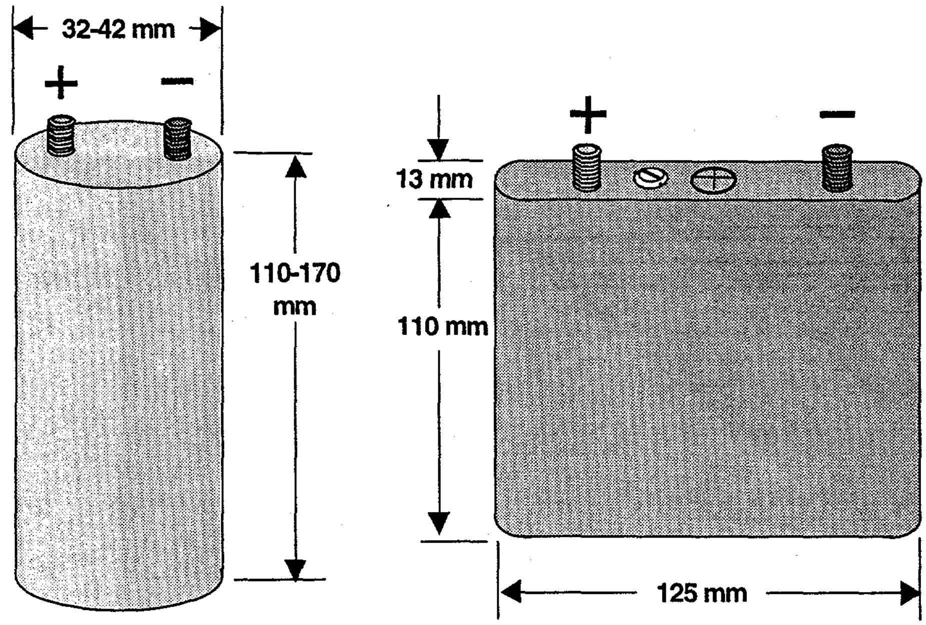

Figure 1. Cylindrical and Flat Lithium-ion Cells for PNGV Application, 10-Ah Capacity (1-h rate), 0.4 kW Power

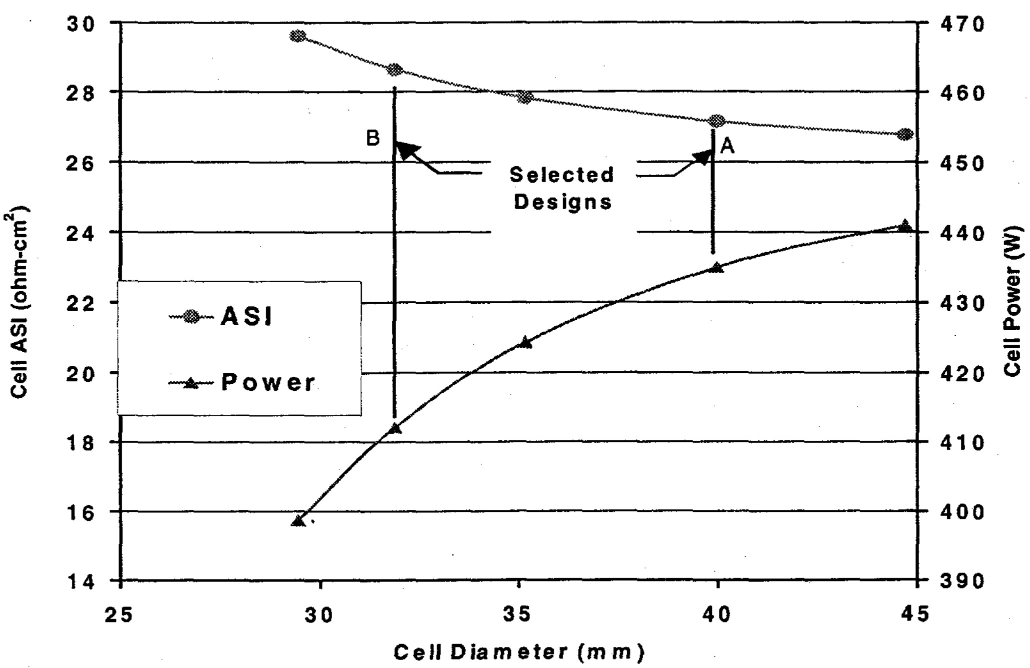

Figure 2. Effect of Cell Diameter upon Power of 10-Ah Cylindrical Cells

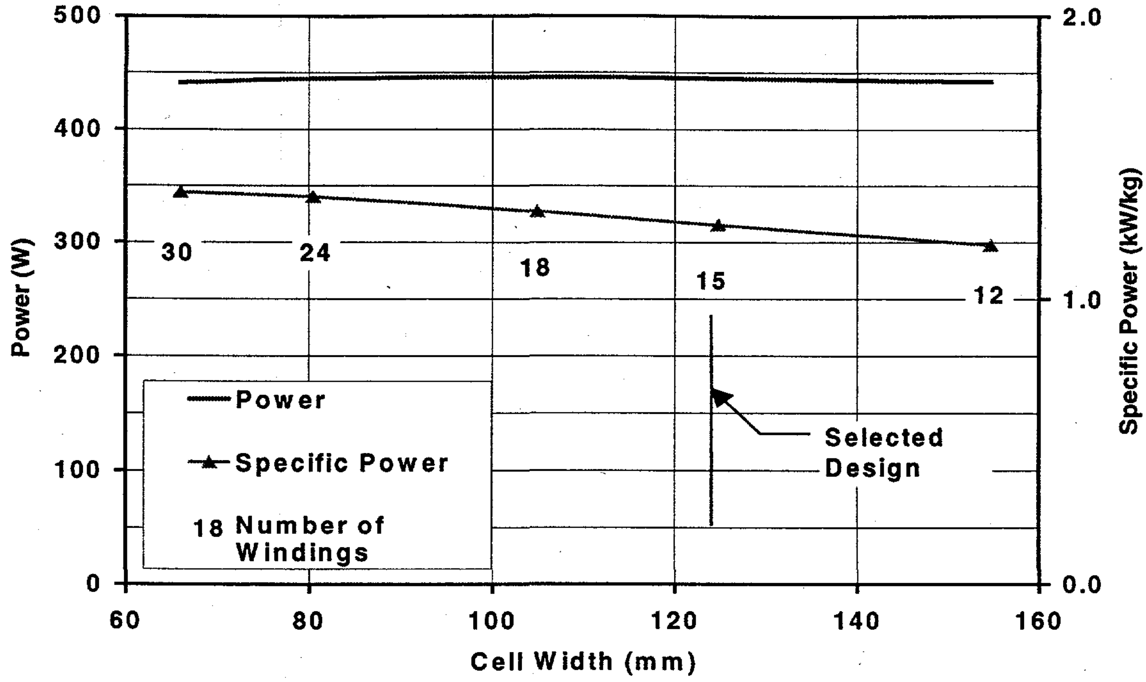

Figure 3. Effect of Cell Width upon Power for 10-Ah Li-Ion Flat Wound Cells

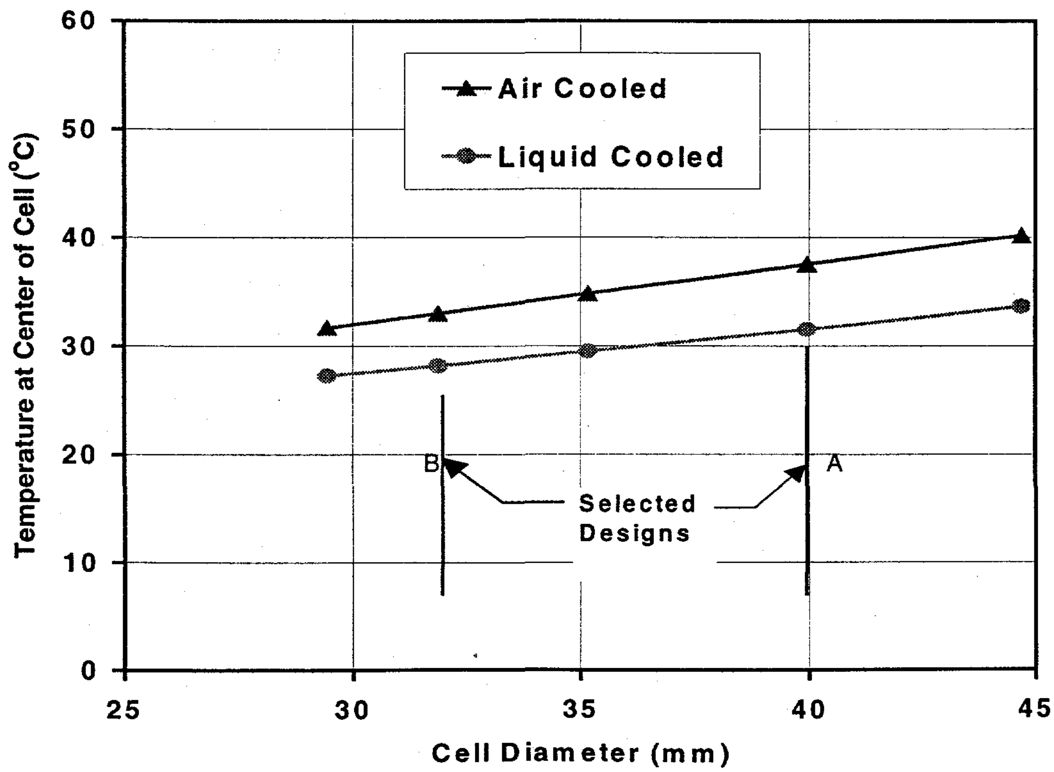

Figure 4. Cooling of Cylindrical Cells Showing Effect of Cell Diameter for Cooling Rate of 5 W and 20°C Coolant Inlet Temperature

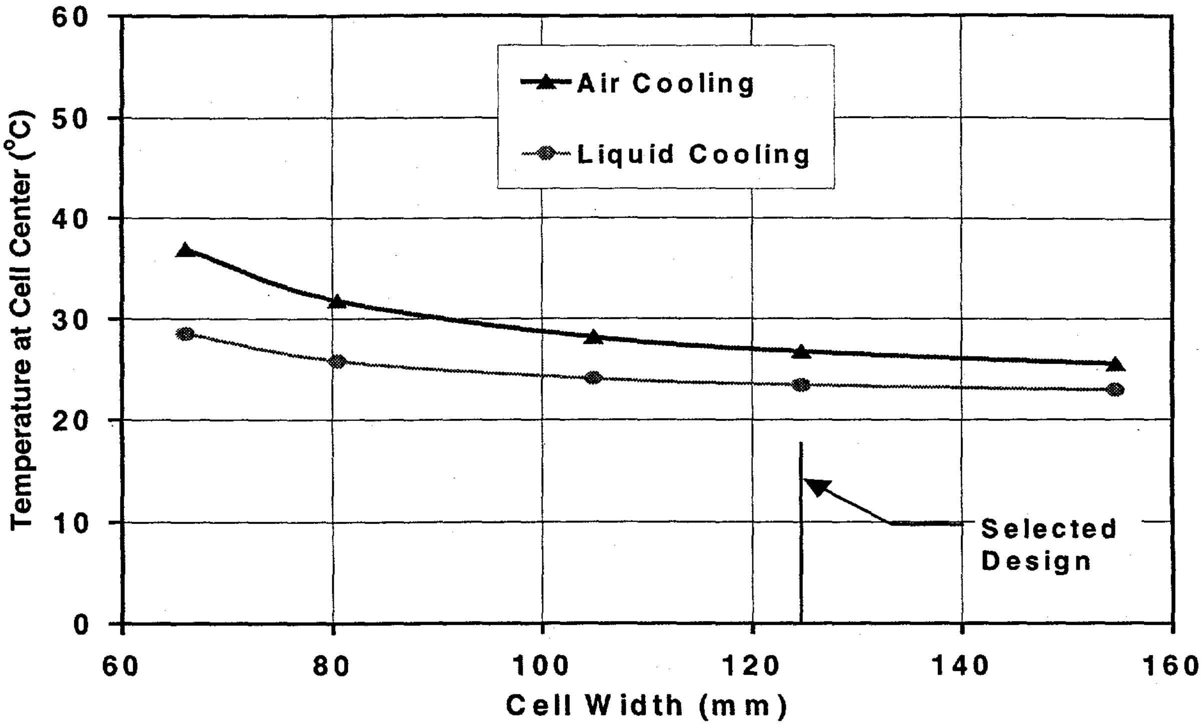

Figure 5. Cooling of Flat Cells Showing Effect of Cell Width
for Cooling Rate of 5 W and 20°C Coolant Inlet Temperature