A METHOD FOR THE ANALYSIS OF HIGH POWER BATTERY DESIGNS

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ABSTRACT

A spreadsheet model for the analysis of batteries of various types has been developed that permits the calculation of the size and performance characteristics of the battery based on and electrode/electrolyte material its internal geometry The method accounts for most of the properties. electrochemical mechanisms in both the anode and cathode without solving the governing partial differential equations. The spreadsheet calculations for a particular battery design are performed much like a battery test in that the C/3 capacity of the battery to a specified cut-off voltage is determined and then the pulse power capability at a given state-of-charge is determined by finding the maximum current density (A/cm2) for which the cell voltage equals a specified minimum value. For a multi-cell module, the module characteristics are calculated using the cell results and packaging input information. The spreadsheet model has been validated for existing lead-acid (Sonnenschein), nickel cadmium (Saft), and nickel metal hydride (Ovonic) batteries for which test data and internal geometry information are available. Various battery designs were then evaluated using the method to show how batteries having high power densities (greater than 500 W/kg) could be designed. The spreadsheet model permitted the determination of the critical design parameters for high power lead-acid, nickel cadmium, and nickel metal hydride batteries.

INTRODUCTION

The primary objective of this work was to develop a method for the analysis of batteries of various types that could be used as a tool to link battery design, performance, especially peak power density and energy density, and cost. There are numerous papers (References 1-5) in the literature that model batteries in great detail starting with the governing partial differential equations that are solved in space, usually in one dimension, and time to determine the concentration and ion current distributions between the electrodes of the battery. These analyzes are valuable for understanding why batteries of a particular design behave as they do, but are cumbersome to use as a design tool to study the effect of battery geometry and material parameters on performance and life cycle and cost related characteristics, such as electrode thickness and area. It was also desired that the method be relatively easily adapted to the analysis of different battery types. One of the motivations for this work was to have a means of analyzing the trade-offs between energy density and peak power density as such trade-offs are often claimed as one of the reasons for using ultracapacitors to load level batteries in electric vehicles.

In order to meet these objectives, it was necessary that the method developed describe the configuration and materials in the cell/module in detail and include the principal electrochemical mechanisms that effect the voltage drop and current flow in the battery. In developing the general, but relatively simple, model of the battery discussed in this paper, the works presented in great detail in References (1-6) were invaluable as sources of electrode material and electrolyte properties and discussions of the basic governing equations. Second sources of valuable information were various battery test reports, especially those from the Idaho National Engineering Laboratory (References 7-8) that showed the discharge characteristics of several type of batteries and the battery internal design parameters based on post-test tear-This information was invaluable in down studies. determining input data for the present calculations and permitting the validation of the method developed for specific battery designs. Validation was done in terms of comparing calculated and measured values for Ah capacity and energy density for constant current discharges, peak power density for a specified voltage cutoff, cell resistance, and module weight and dimensions

GENERAL APPROACH

The intent was to develop battery models using spreadsheet software (EXCEL) that described the essence of the electrochemical mechanisms in the battery without solving the governing partial differential equations. It was also desired that the model could be exercised to determine the performance characteristics of a particular battery design in much the same way that a battery would be tested - that is discharged at constant current to a specified cut-off voltage and then discharged at high currents for short pulses to determine its peak power density and resistance. These objectives were met in the following way. Battery state-ofcharge, given in terms of active material utilization, was used in place of discharge time. Useable Ah capacity for a specified current density (A/cm2) was determined by varying the material utilization fraction at that current until the voltage at that utilization fraction equaled the specified cut-off voltage. The maximum current density (A/cm2) and thus the peak power density at a specified depth-of-discharge for a particular battery design was found by varying the current density until the calculated voltage at that state-of-charge (material utilization fraction) equaled the specified cut-off voltage for short pulses. Hence running the spreadsheet is much like testing a battery in that one varies the current (A/cm2) and observes the resultant voltage behavior of the battery.

The battery cell is described in terms of its component parts: (1) anode, (2) cathode, and (3) separator/electrolyte (see Figure 1). Each of the parts is prescribed in terms of its geometry (thickness) and material properties (chemistry, porosity, surface area, density, specific resistance, etc.). The anode and cathode are made up of a current collector or grid and an active electrode layer. The characteristics of the grid and active layer are specified individually. The chemistries of the anode and cathode materials are given in terms of the molecular weight, charge number, and Ah/gm of the active materials and products and the standard potentials and reference exchange currents needed to describe the Tafel equation for the electrode surface interfaces. Provision is made for inert binders in the electrode layers. The separator is specified in terms of its thickness, porosity, and specific resistance. The electrolyte is described in terms of its density, ionic resistivity, diffusion coefficient, and transference number. The voltage changes in the anode, cathode, and separator are calculated separately for the specified current density and active material utilization fraction, which are inputs to each trial calculation of the spreadsheet. The voltage changes across each part of the cell include the effect of changes in the ion concentration in the electrolyte and the active material availability at the electrode surfaces on the electrode open circuit potentials and exchange currents as the battery discharges. Average concentration and voltage gradients are calculated for each electrode from the required ion fluxes at the specified current density (A/cm2). The concentration and voltage changes are then calculated from the product of the average gradient and mean electrode thickness. After the cell characteristics are determined on a unit area (cm2) basis, the area required in an actual cell to meet the specified Ah capacity is calculated. The weight and size of the various component parts of the cell are then determined and the energy density and peak power density calculated. The output of the spreadsheet yields a complete description of the cell and its performance. The final step in the calculation

is to combine the cells into a module of a prescribed voltage and to calculate the characteristics of the module.

This general approach has been applied to lead-acid, nickel cadmium, and nickel metal hydride batteries. Input data for those battery types and selected results from the spreadsheet calculations are discussed in the next section.

APPLICATION OF THE METHOD TO SPECIFIC BATTERY TYPES AND DESIGNS

Validation of the Method

This approach to battery analysis has been validated by applying it to several existing batteries for which there were test data and reasonable knowledge of the battery internal construction and materials characteristics. The batteries selected were the Sonnenschein DF 6V-160 sealed lead-acid battery (Reference 8), the SAFT SEH-5-200 nickel cadmium battery (Reference 9), and the Ovonic 14V-90Ah nickel metal hydride battery (References 9-10). Each of these batteries was analyzed using the spreadsheet model. In each case, the battery positive and negative plates were sized to yield the measured C/3 Ah capacity. When information on thicknesses of the grids and active layers of the electrode plates were available, it was used in setting up the inputs for the analysis of the battery. As shown in Tables 1 and 2, which are listings of the inputs for the Sonnenschein and Ovonic batteries, the batteries are described in considerable detail in terms of their construction, materials, and electrochemical characteristics. For the three batteries being analyzed, some of the input quantities were known with relatively little uncertainty while there was considerable uncertainty for some of the input parameters. In the latter instances, the input parameters were varied over physically appropriate ranges and values were determined that yielded a set of battery cell/module characteristics that were consistent with the known weight, dimensions, and performance of the battery. As shown in Table 3, the spreadsheet model yielded results in good agreement with the actual/measured characteristics of the three batteries being analyzed. No attempt was made to refine the inputs for each battery to bring the overall agreement between the calculated and measured values to better than about 10%. because of the large number of inputs involved. In future work, it is planned to contact the battery manufacturers directly and attempt to get from them actual values of dimensions and material properties for their batteries. Nevertheless, the good agreement shown in Table 3 indicates the general validity of the approach for battery analysis and justifies the application of the method to assess the performance of advanced battery designs.

Application to Various Battery Designs

Lead-acid batteries.

The method has been applied to a series of lead-acid battery designs as shown in Table 4. The thicknesses of the grids/current collectors, plates, and separator have been varied over wide ranges. The Ah capacity of the cells has also been varied. The results shown in Table 4 indicate that it should be possible to design lead-acid batteries having very high power density with a relatively small sacrifice in energy density. This requires that the current collectors and plates be very

thin compared with thicknesses used in most existing batteries. The results for the small 1.2 Ah design, which is intended to represent that of the Bolder Technologies battery, shows performance close to that reported in Reference (11) for that battery/cell. For the lead-acid batteries, the separator thickness and grid openness are particularly critical parameters. The results indicate that a high power, high energy density lead-acid battery should utilize a current collector with large openness and distributed current collecting capability, like a foam. A thin foil, like that used in the Bolder Technology battery yielded high power density, but lower energy density. Thin plates in the lead-acid batteries seem to result in significantly higher active material utilization than is achieved in thicker plate batteries, such as the Sonnenschein DF 6V-160. A key factor that is not addressed in the present work is the effect of the thin plates on battery cycle life. If, as seems likely, achieving long cycle life with the very high power density designs is difficult or nearly impossible, the primary advantage of using ultracapacitors to load level the "energy" battery in an electric vehicle will be to extend its cycle life. The high power density batteries also have high plate area per Ah and thus high cost.

Nickel cadmium batteries.

A series of nickel cadmium battery designs were also evaluated using the spreadsheet model. The results shown in Table 5 indicate that high power density (W/kg) can be achieved with nickel cadmium batteries. As with lead-acid batteries, high power density requires thin plates. However, unlike lead-acid batteries, the power density in nickel cadmium batteries is much less sensitive to current collector openness and separator thickness. It does not seem possible to achieve the very high power densities of 2000 W/kg and greater than is the case for the thin film lead-acid batteries. Also the results in Table 5 indicate that achieving high power in nickel cadmium batteries will require a sacrifice in energy density. However, it seems likely that it will be less difficult to achieve high cycle life with thin plate nickel cadmium

batteries than with thin plate lead-acid batteries.

Nickel metal hydride batteries.

Nickel metal hydride batteries designs were also evaluated using the spreadsheet model. The results of the calculations are shown in Table 6. The Ah capacity of the cells was varied from 90 to 5 Ah for plate thicknesses between .008 and .06 cm. The critical material parameters for this battery are the percent hydrogen storage and particle radius of the hydride material in the anode. The spreadsheet results indicate that high power density (800-900 W/kg) nickel metal hydride cells can be designed using thin plates and anode material having a 2% hydrogen storage capacity and a small particle radius of 20 microns. High power density can be achieved using either foil type or foamed open sheet electrodes, but it appears that using thin foil as the current collector results in an energy density penalty compared with the open electrodes. As in the case of the other battery types, a primary consideration for the nickel metal hydride batteries is the cycle life of the thin film batteries needed to achieve power densities of 500-1000 W/kg.

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Figure 1: Cell Geometry



Table 1: Model Inputs for Lead-Acid Batteries

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	138 Ah	3	cells/modu	le
Anode (ne	gative plate of spongy F	Pb)		
Grid (curre	ent collector)	_		
	Density (grm/cm3)			11.3
	resistance (ohm-cm2)		- · ·	0.00072
	Thickness (cm)			0.0075
	Inickness (Ch)			0.0313
-	iopenness (76)			<u> </u>
Active mat	terial (after formation)			
	Density (gm/cm3)			11.3
_	PbSo4 density (gm/cm	13)		6.3
	Thickness (cm)			0.15
	Initial porosity (100%)			0,75
	Surface area (cm2/cm	31		2 50F+04
	theoretical Canacity (A	b(am)	<u> </u>	0 250
	concitio endeistance (a	hm cm)		2.005.05
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	Standard potential (Vo	2005)	L	0.344
	Reference exchange c	urrent (AVCI	n2)	8.00E-06
	Reference concentrate	on (moles/li	ter)	4.9
	Torquosity factor			1.5
	Molecular weight (gm-	mole)		207
	grid thickness/plate thi	ckness		0.65
	transfer coefficient		· · · · · · · · · · · · · · · · · · ·	0.5
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Grid (aum	et collectori		<u> </u>	<u> </u>
- Cona loune	density (nor (and 2)		f ———	44.21
	density (gm/cm3)		ļ	11.3
	resistance (onm-cm2)	Ļ		0.00072
	Thickness (cm)	L		0.108
	openness (%)			70
Active mat	terial			
	density (gm/cm3)			9.7
	PbSo4 density fam/cm	n3)		6.3
	Thickness (cm)			0 167
	Initial Describe			0.107
	Initial Porosity			0.7
	Surface area (cm2/cm	3)		2.50E+05
	theoretical capacity (A	h/gm)		0.224
	specific resistance (oh	<u>m-cm)</u>		2.00E-05
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	Statioard potential from	5		1.0202
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Separator	Schoold poestication for Schoold poestication for Reference exchange c Reference concentration Torquosity factor Molecular weight grid thickness/plate thi transfer coefficient density (gm/cm3) thickness (cm) porosity specific resistance (ch (suffuric acid) initial density (gm/cm3) solvent/ions water ionic resistivity (Ohn-c reference ion concent reference ion concent reference ion concent reference diffusion coe Postive ion transference initial ion concentration of the discharge set type of discharge set type of discharge set type of discharge estimated state-of-cha cutoff-vottage/cell minimum vottage/cell estimated current dems	S) urrent (A/cr on (moles/li ckness ckness) H SO4, H+ m) ation (mole fficient (cm enumber 1 (moles/cn figdc3=3 (t in) rge tt high pow ity at C/3 (/ density (A/	n2) ter) s/liter) s/liter) 2/sec) 3) 7/3), flgdc3- 3) er Vcm2) cm2)	1.0282 6.00E-07 2.39 0.65 0.5 0.5 0.5 0.5 0.5 0.5 0.194 0.001 1.258 0.05 4.9 2.00E-05 0.72 4.90E-03 2.00E-05 0.72 4.90E-03 1.133 0.012 0.65
electrolyte	Schrode poertain (to Schrode poertain (to Reference exchange c Reference concentrati Torquosity factor Molecular weight grid blickness/plate thi transfer coefficient density (gm/cm3) thickness (cm) porosity specific resistance (oh (suffuric acid) initial density (gm/cm3 solvent/ions water ionic resistivity (Ohm-c reference ion concent reference ion concentration of the discharge set type of discharge set mated current dens estimated current dens restimated max current nominal cell voltage	(A/cr on (moles/li ckness ckness m-cm)) H SQ4, H+ m) ation (mole fifcient (cm e number o (moles/cn in) figdc3=3 (in) figdc3=3 (in) figdc3=3 (in)	n2) ter) Sitter) Sitter) 2/sec	1.5282 6.00€-07 2.399 0.655 0.55 0.05 0.05 0.05 0.194 0.86 0.005 1.258 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
Separator electrolyte	Schnold poeting the section of the s	(A/cr an (moles/fi ckness ckness m-cm) H SO4, H+ m) ation (mole fficient (cm an) ation (cm an) (cm an) (cm an) (cm	n2) ter) sfiter) sfiter) 2/sec) 33) 5/3), figdc3- 5/3), figdc3- 5/3, figdc3- com2) com2) e	1.5282 6.00€-07 2.399 0.655 0.05 0.05 0.05 0.194 0.65 0.05 0.194 0.001 1.258 0.05 4.9 2.00€-05 0.72 4.30E-03 0.05 4.9 2.00€-05 0.72 4.30E-03 0.05 1.333 0.012 0.172 0.172 2.2 0.4
Separator electrolyte	Schnold poetical for Schnold poetical for Reference concentrati Torquosity factor Molecular weight grid thickness/plate thi transfer coefficient density (gm/cm3) thickness (cm) porosity specific resistance (oh (suffuric acid) initial density (gm/cm3 solvent/ions water ionic resistivity (Ohn-c reference iffusion coe Postive ion transferenc initial ion concentration of the discharge set type of discharge set type o	s) mrent (A/cr on (moles/li ckness m-cm)) H SQ4, H+ m) ation (mole fificient (cm re number (moles/cn figdc3=3 ((in) rge at high pow ity at C/3 (density (A/ // discharg	n2) ter) s.fiter) 2/sec) 3) 7/3), flgdc33 7/3), flgdc33 er Vcm2) cm2) e	1.0282 6.00E-07 2.39 0.65 0.5 0.05 0.194 0.00 1.256 0.05 0.00 1.256 0.00 1.256 0.00 1.256 0.05 4.9 2.00E-05 0.72 4.90E-03 3.0012 0.72 4.90E-03 0.05 1.333 0.012 0.175 1.333 0.012 0.172 0.4
electrolyte	Schnold poeting the set of the se	(A/cr on (moles/lin ckness ckness m-om)) H SO4, H+ m) ation (mole fificient (cm e number n (moles/cn figdc3=3 (in) rge thigh power ifly at C/3 (density (A/ / 3 discharg	n2) ter) Silter) Z/sec) Z/sec) 3) Z/3), flgdc3 Gray Vcm2) cm2) e	1.0282 6.006-07 4.9 1.5 239 0.65 0.05 0.05 0.194 0.65 0.05 0.194 0.8 0.001 1.258 0.5 4.9 2.006-05 0.72 4.90E-05 0.75 1.33 0.06 0.6 1.75 1.33 0.012 0.172 2.2 0.4
Separator electrolyte	Schrodt poerful to the second	(A/cr on (moles/li ckness ckness m-om) H SO4, H+ m) ation (mole fficient (cm m) ation (mole fficient (cm m) ation (mole fficient (cm m) ation (mole fficient (cm m) ation (mole fficient (cm fficient (cm m) ation (mole fficient (cm m) ation (mole fficient (cm fficient (cm fficint (cm fficient (cm fficient	n2) ter) sfiter) 2/sec) 3) 2/sec) 3) 2/3), figdc3= 0/3), f	1.5282 6.00€-07 2.399 0.65 0.05 0.05 0.05 0.05 0.194 0.65 0.05 0.05 0.194 0.001 1.258 0.05 0.001 1.258 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.
electrolyte	Scandard potential (tod Scandard potential (tod Reference exchange c Reference concentrati Torquosity factor Molecular weight grid thickness/plate thi transfer coefficient density (gm/cm3) thickness (cm) porosity specific resistance (oh (suffuric acid) initial density (gm/cm3 solvent/ions water ionic resistivity (Ohm-c reference ion concentr reference diffusion coe Postive ion transferenc initial ion concentration of the discharge set type of discharge material utilization at C rameters plate height(cm) plate width (cm)	(A) ckness ckness m-cm) H H H SQ4, H+ m) ation (mole fificient (cm rge figdc3=3 (cm figdc3=3 (cm) figdc3=3 (cm)	n2) ter) s.niter) 2(sec	1.5282 6.00€-07 2.399 0.655 0.55 0.05 0.055 0.194 0.88 0.0001 1.258 0.55 4.9 0.05 0.55 4.9 0.05 0.55 4.9 0.05 0.55 4.9 0.05 0.55 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0
Separator electrolyte	Schnold poeting the section of the s	(A/cr on (moles/fi ckness ckness m-cm) H SO4, H+ m) ation (mole fficient (cm e number) n (moles/cm figdc3=3 (in) rge at high pow ity at C/3 (density (A/ / density (A/	n2) ter) Siliter) 2/sec) 3) 3) 3) 3) 3) 3) 3) 3) 3) 3) 3) 3) 3)	1.5282 6.00E-07 2.399 0.655 0.05 0.05 0.194 0.65 0.05 0.194 0.65 0.75 0.05 0.194 0.001 1.258 0.05 0.72 2.00E-05 0.72 2.00E-05 0.75 1.75 1.33 0.012 0.66 1.772 2.00E-05 0.72 2.00E-05 0.72 1.733 0.012 0.66 1.75 1.33 0.012 0.66 1.75 1.33 0.012 0.66 0.66 0.72 0.72 0.72 0.72 0.72 0.72 0.72 0.72
Separator electrolyte	Schrodt poerial (to a change c Reference exchange c Reference exchange c Reference concentrati Torquosity factor Molecular weight grid thickness/plate thi transfer coefficient density (gm/cm3) thickness (cm) porosity specific resistance (ch (suffuric acid) initial density (gm/cm3 solvent/lons water ionic resistivity (Ohm-c- reference ion concentr reference diffusion coe Postive ion transferenc initial ion concentration of the discharge set type of discharge set imated state-of-cha cutoff-vottage/cell minimum vottage/cell minimum vottage/cell minimum vottage/cell material utilization at C cameters plate height(cm) plate width (cm)	(A/cr on (moles/li ckness ckness m-cm) H SO4, H+ m) ation (mole fficient (cm e number (moles/cn ffigdc3=3 ((in) rge thigh power ity at C/3 (/ density (A/ // density (A/) density (A/) density (A/) d	n2) ter) sfiter) 2/sec) 3) 2/3), figdc3: cr Vcm2) cm2) e e	1.0282 6.00€-07 2.39 0.65 0.5 0.05 0.05 0.194 0.65 0.05 0.194 0.001 1.258 0.05 0.001 1.258 0.05 0.001 2.00€-05 0.72 4.90E-03 0.05 0.72 4.90E-03 0.05 0.72 4.90E-03 0.05 0.72 4.90E-03 0.05 0.72 4.90E-03 0.05 0.72 4.90E-03 0.05 0.72 4.90E-03 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.
electrolyte	Schnold poeting to the set of the	(A/cr on (moles/lin ckness ckness m-cm)) H HSQ4, H+ m) ation (mole fifticient (cm e number n (moles/cn in) figdc3=3 (c in) figdc3=3 (c in) figdc3=3 (c in) figdc3=3 (c in) figdc3=3 (c) figdc3=3 (c) fi	n2) ter) Sitter) Sitter) 2/sec	1.5282 6.00€-07 2.39 0.655 0.55 0.05 0.05 0.194 0.88 0.0011 1.258 0.5 4.9 2.00€-05 0.72 4.90E-05 0.05 0.72 4.90E-05 0.05 0.72 4.90E-05 0.72 2.00E-05 0.72 2.00E-05 0.72 2.00E-05 0.72 2.00E-05 0.72 2.00E-05 0.72 2.00E-05 0
Separator electrolyte	Schnold poeting to the set of the	s) unrent (A/cr on (moles/fi ckness m-cm)) H SO4, H+ m) ation (mole fficient (cm en umber) n (moles/cm figdc3=3 ((in) rge at high pow ifly at C/3 (density (A/ density (A/ is) rge at high pow ifly at C/3 (density (A/ is) rge at high pow	n2) ter) sfilter) 2/sec) 33) 2/3), flgdc3 33) cr(2) sec) cm(2) e	1.5282 6.00€-07 2.399 0.655 0.05 0.05 0.194 0.65 0.05 0.194 0.65 0.72 1.258 0.05 0.194 0.001 1.258 0.05 0.194 0.001 1.258 0.05 0.72 2.00E-05 0.72 3000 0.66 1.75 3.00 0.05 0.72 4.90E-05 0.72 3000 0.66 1.75 3.00 0.05 0.72 4.90E-05 0.72 4.90E-05 0.72 4.90E-05 0.72 4.90E-05 0.72 4.90E-05 0.72 4.90E-05 0.72 4.90E-05 0.72 4.90E-05 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.
Condition	Schnold poetical (to Schnold poetical (to Reference concentrati Torquosity factor Molecular weight grid thickness/plate thi transfer coefficient density (gm/cm3) thickness (cm) porosity specific resistance (oh (suffuric acid) initial density (gm/cm3 solvent/ions water ionic resistivity (Ohn-c reference diffusion coe Postive ion transferenc initial ion concentration of the discharge set type of discharge material utilization at C rameters plate height(cm) plate width (cm) container thickness (cr container thickness (cr) terminal diameter (cm) terminal height(cm)	s) unrent (A/cr on (moles/lin ckness m-cm)) H HSQ4, H+ m) ation (mole fifscient (cm re number (moles/cn figdc3=3 ((in) rge at high pow ity at C/3 (density (A/ //3 discharg	n2) ter) s/liter) 2/2sec) 3) C/3), flgdc3- C/3), flgdc3- cr V/cm2) crm2) e	1.5282 6.00€-07 2.399 0.655 0.5 0.05 0.05 0.194 0.65 0.05 0.194 0.68 0.0001 1.258 0.5 4.9 2.00€-05 0.72 4.90E-03 0.5 0.72 4.90E-03 0.65 0.72 4.90E-03 0.65 0.72 4.90E-03 0.65 0.72 4.90E-03 0.65 0.72 4.90E-03 0.65 0.72 4.90E-03 0.72 4.90E-03 0.05 0.72 4.90E-03 0.05 0.72 4.90E-03 0.05 0.72 4.90E-03 0.05 0.72 4.90E-03 0.05 0.72 4.90E-03 0.72 4.90E-03 0.05 0.72 4.90E-03 0.05 0.72 4.90E-03 0.05 0.72 4.90E-03 0.05 0.72 4.90E-03 0.05 0.72 4.90E-03 0.05 0.72 4.90E-03 0.05 0.72 4.90E-03 0.05 0.72 4.90E-03 0.05 0.02 0.72 4.90E-03 0.05 0.02 0.05 0.72 4.90E-03 0.05 0.05 0.05 0.72 4.90E-03 0.05 0.05 0.05 0.72 4.90E-03 0.05 0.05 0.05 0.05 0.72 4.90E-03 0.05 0.05 0.05 0.05 0.05 0.05 0.72 4.90E-03 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.
electrolyte	Schnold poerful (1997) Schnold poerful (1997) Reference exchange c Reference concentration Torquosity factor Molecular weight grid thickness/plate thi transfer coefficient density (gm/cm3) thickness (cm) porosity specific resistance (oh (suffunc acid) initial density (gm/cm3) solvent/ions water ionic resistivity (Ohn-c reference ion concentration of the discharge Set type of discharge Temperature (deg Kekl estimated state-of-cha cutoff-voltage/cell minimum voltage/cell minimum voltage/cell minimum voltage/cell minimum voltage/cell minimum voltage/cell minimum voltage/cell minimum voltage/cell minimum voltage/cell cestimated max current nominal cell voltage material utilization at C rameters plate height(cm) plate width (cm) container thickness (cr container density (gm/c terminal diameter (cm) terminal miniph (cm) ratio intercell/plate con	s) unrent (A/cr on (moles/li ckness ckness m-om)) H SO4, H+ m) ation (mole fficient (cm en umber n (moles/cn figdc3=3 (in) rge thigh power ity at C/3 (density (A/ / density (A/ / 3 discharg	n2) ter) Silter) Silter) Z/sec) Z/sec) Z/sec) Z/sec) Z/sec) Cm2) cm2) e e e e e	1.2222 6.00E-07 2.339 0.655 0.05 0.05 0.05 0.05 0.05 0.05 0.0

Table 2: Model Inputs forNickel Metal Hydride Batteries

1

	I BRIAN I Icelis/modul	e
	Anode (negative plate of metal hydride)	
· ·	Grid (current collector-nickel screen)	
	Density (gr/m/cm3)	88
	resistance (ohm-cm)	0.00075
	Thickness (cm)	0.005
	openness (%)	90
	Active material (after formation)	
	Density (gm/cm3)	5.69
	density (gm/cm3) of hydride after discharge	5.69
	Thickness (cm)	0 016
	Initial porosity (100*%)	0.6
	Surface area (cm2/cm3)	2.00E+03
	theoretical Capacity (Ah/gm)	U.208 AN
	specific ressistance (ohm-cm)	2.002-05
	Standard potential (Volts)	-0.0
	Reference exchange current (A/cm2)	2.04E-04
	Reference concentration (moles/liter)	15
	Torquosity factor	50
	Molecular weight (gm-mole)	0 33
	grid thickness/platectickness	0.35
	transfer coefficient	0.0
	hydride particle radius (cm)	5 005 10
	hydride alfusion coefficient (cm2/sec)	3.002.10
	initial M concentrations (moles M(cm2)	0 1138
	Innual in concentration (moles rychio)	20
	number of terms in amusion solution	0.67
	order or reaction for P1	0.538
· · · · · · · · · · · · · · · · · · ·	ineoretical capacity (Arvgm) -specified 361	+
	cathode (positive plate of NOUTH on foamed nickel)	<u> </u>
	Gina (current collector)	8.8
	joensny (griverna)	0 00072
	Thickness (cm)	0.03
	(hickness (cffi)	90
	openness (%)	
	Active material	5 826772
	density (gm/cm3)	1 83
	Ni(OH)2 density (gm/cm3)	0.045
	Thickness (cm)	0.65
	Initial Porosity (%)	4 005+03
	Surface area (cm2/cm3)	0.201
	theoretical capacity (Alvgm)	2005.05
	specific resistance (ohm-cm)	2.000-00
	Standard potential (Volis)	6105.05
	Reference exchange current (Avcinz)	71
	Terrustik factor	15
	Molecular weight	92
	and thickness/plate thickness	0.9
~	Imaster coefficient	0.5
	Casambre	
		1 01
	density (gm/cm3)	0.1
	thickness (cm)	0.0/5
	porosity	0.0
	specific resistance (onm-cm)	0.00
	++++++++	++
		++
		1 745
	Inmail density (gm/cm.3)	
	solvenulons water Utt-, HT	1.87
	ionic resistivity (Unm-cm)	7 1
	reference diffusion conficient (cm2/sec)	2575-05
	Postive ing transference number	0.78
	ligitial inconcentration (molec/cm ³)	5.00E-03
	conditions for the discharge	1
	set type of discharge figde=3 (C/3) figde3=1 may now	er
	Temperature (deg Kelvin)	300
	estimated state-of-charge	0.06
	cutoff voltage/cell	1 1
	minimum voltage/cell at high nower	0.8
	estimated ourgent density at CB (Alom?)	0.064
	estimated max current density at CVC (VCI12)	0 12
	nominal cell voltage	1.3
	material utilization at C/3 discharge	0 94
	module parameters	
	plate beight(cm)	15
	plate width (cm)	85
	container thickness (cm)	0.02
	cell divider thickness (cm)	0,0001
	stainless steel container density (cm/cm3)	7.75
	terminal radius (cm)	0.3
	terminal height (cm)	1
	terminal height (cm)	1

TABLE 3: VALIDATION RE SULTS FOR THREE BATTERY TYPES

Sealed Lead-Acid Battery Sonnenschein DF-6V-160							
Actual Model							
c/3 Capacity (Ah)	138	138					
Weight (kg)	32.4	32.8					
(wh/kg) c/3	25	25.2					
Length (cm)	25.9	22.7					
No. of Plates	15-16	15					
(w/kg) max at 75% DOD	160	192					
Resistance (ohms)	.00064/cell	.00086/cell					

Nickel Cadmium Battery SAFT SEH-5-200

	Actual	Model
c/3 Capacity (Ah)	204	204
Weight/(kg)	24.9	22.7
(wh/kg)c/3	55.0	49.9
Length (cm)	24.5	28.0
No. of Plates	15-16	15
(w/kg) max at 75% DOD	160	192
Resistance (ohms)	.00042/cell	.000433/cell

Nickel Metal Hydride Ovonic 1.3V, 90 Ah

	Actual	Model
c/3 Capacity (Ah)	90	90
Weight (kg)	1.62	1.8
(Wh/kg)c/3	70	63
Length (cm)	3.7	3.4
No. of Plates	-	17
(W/kg)max at 75% DOD	>220	278
Resistance (A)	.00105/cell	.0007/cell

Cell/Module	Ah cm ² Wh/kg) c/3 (W/kg)max area 70% DOD cm ² cell	.0347 25.2 83 3075	0168 46.9 364 2975	.0100 55.3 1492 4977	.0068 37.5 1583 7375	.0037 26.1 2880 323	
Separator	th (cm)	.105	.075	.05	.03	.015	
Cathode Cathode	tų (can) porosity	.167 .7	.06 .7	.03 7	.025 .7	.0125 .7	
	porosity	.75	.70	.70	.70	.70	
Anode	th (cm)	.15	.05	.03	.02	.0125	
Grid	th (cm) % open	0975 70	.04 80	.01 80	005 0	.0025 0	
	(Ah)c/3	138,12V	50,12V	50,12V	50,12V	1.2,2V	

TABLE 4: MODELING RESULTS FOR VARIOUS DESIGNS OF SEALED LEAD-ACID BATTERIES

TABLE 5: MODELING RESULTS FOR VARIOUS DESIGNS OF NICKEL CADMIUM BATTERIES

Cell/module	ah/cm ² (Wh/kg)c/3 (Wh/kg)mg area cm ² /cell	.038 69 183 5337	.038 69 183 5337	.008 45 490 6263	.0054 47 576 1854	
	porosity	9.	9.	.4	4.	
Cathode	th (cm)	.050	.080	.012	.008	
Separator	th (cm)	.1	.1	.075	.025	
	porosity	.67	.67	.5	9.	
Anode	th (cm)	.044	.060	.010	700.	
Grid/Foam	th (cm) % open	.004 10	.004 10	.008 90	.005 90	
	(Ah)c/3	204,6V	204,6V	50,6V	10,6V	

TABLE 6: MODELING RESULTS FOR VARIOUS DESIGNS OF NICKEL METAL HYDRIDE BATTERIES

	=	Γ						
	area cm²/ce	2734	1953	5524	4833	2228	1311	
	(W/kg)max 70% DOD	301	440	300	443	834	905	
	(Wh/kg)c/ 3	9	ω	61	71	37	60	
Module/Cell	Ah/cm²	.033	.046	.016	.0186	.0045	.0038	
	porosity	с.	.5	.65	.70	.70	.70	
Cathode	th (cm)	.06	.06	.045	.045	.0125	600	
	%Н ²	1.25	1.75	1.75	2.0	2.0	2.0	
	rp(u)	30	20	30	20	20	20	
	porosity	.6	9.	.6	9.	.70	02.	
Anode	th (cm)	.045	.045	.015	.015	.0125	.008	
Grid	th (cm) % open	.012 92	.012 92	.005 92	.005 92	.0025 0	.005 90	
	(Ah)c/3	90,1.3V	90,1.3V	90,1.3V	90,1.3V	10,1.3V	5,1.3V	

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