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Comparison of Advanced Battery Technologies for Electric Vehicles

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ABSTRACT

Battery technologies of different chemistries, manufacture and geometry were evaluated as candidates for use in Electric Vehicles (EV). The candidate batteries that were evaluated include four single cell and seven multi-cell modules representing four technologies; Lead-Acid, Nickel-Cadmium, Nickel-Metal Hydride and Zinc-Bromide. A standard set of testing procedures for electric vehicle batteries, based on industry accepted testing procedures, and any tests which were specific to individual battery types were used in the evaluations. The batteries were evaluated by conducting performance tests, and by subjecting them to cyclical loading, using a computer controlled charge - discharge cycler, to simulate typical EV driving cycles. Criteria for comparison of batteries were: performance, projected vehicle range, cost, and applicability to various types of EVs. The four battery technologies have individual strengths and weaknesses and each is suited to fill a particular application. None of the batteries tested can fill every EV application.

INTRODUCTION

The Center for Electrochemical Systems and Hydrogen Research (CESHR) at Texas A&M has been doing fundamental research on energy conversion and storage devices since 1987. During this period , the center has acquired 7 electric vehicles. The testing of commercially available and advanced electric vehicle batteries was started in 1990. Today's storage battery powered EVs have ranges of 30 to 150 miles per charge. The addition of a hydrogen fuel cell or other main energy device can increase this range , but batteries would still be needed for load leveling and acceleration. Each type of electrically driven vehicle requires different battery performance characteristics. For example, for battery powered EVs the important performance characteristics are that they have a high energy and power density. Energy density translates to the range of the vehicle and power density relates to the acceleration and hill climbing ability. Hybrid EVs require very high power density batteries that have a weak current-voltage relationship such that the voltage is relatively independent of load and will therefore not overload the main energy device as load changes. The batteries in a hybrid EV will be mainly used for load leveling (peaking power) for the main energy device. There are many candidate technologies with different characteristics. Important characteristics include: performance, cost, ruggedness, toxicity and life.

The objective of the investigation reported here was to determine the strength and weaknesses of various battery technologies for EV use. Each EV application and configuration may have different requirements and stress different characteristics of the battery. The objective was satisfied by first identifying a standard set of testing procedures for electric vehicle batteries based on industry accepted testing procedures, and any tests which are specific to individual battery types. The batteries were then evaluated by conducting performance tests, and by subjecting them to cyclical loading using a computer controlled charge-discharge cycler to simulate typical EV driving cycles. Performance characterizations and/or life evaluations were conducted on four single cells and seven 3 to 72 cell modules representing four technologies, (Nickel-Cadmium, Nickel-Metal Hydride, Lead-Acid, and Zinc-Bromide). Comparison of the batteries was based on: performance, projected vehicle range, cost and applicability to various types of EVs. The experimental apparatus is described followed by detailed descriptions of the performance characterization tests. Results are presented in graphical and tabular form to a allow an evaluation of each battery technology relative to the requirements of the various EV types.

EXPERIMENTAL APPARATUS

Loading of the batteries was accomplished with a computer controlled battery cycler. The computer controlled cyclers are capable of constant-current, constant-voltage, and constant-power modes of charge and discharge on the batteries.

The power system test programs may contain up to fifty steps, with each step being a charge, discharge, or rest. This enables the user to program the cycler for steady-state and dynamic modes of operation. The cycler measures current, voltage and temperature and calculates power, amp-hours and watt-hours. Cycles such as the Simplified Federal Urban Driving Schedule (SFUDS), Society of Automotive Engineers (SAE) cycles, and any power vs. time cycle can be tested in the lab. The range of cyclers used allowed for testing of power systems from AA size batteries to full scale EV batteries.

TESTING PROCEDURE

A testing procedure has been developed to characterize the performance of EV batteries based on national laboratory procedures and equipment available [1]. When a new battery arrives for testing it is physically inspected for any damage or defects. The battery is then weighed and its volumetric dimensions are measured. The electrolyte level is checked and adjusted according to the manufacturers recommendations. The battery is then connected to the cycling equipment and discharged to a known State Of Charge (SOC) before any cycling is begun. Some batteries require a break-in period before the performance testing is started.

Five standard tests are used to characterize the performance of the battery: (1) constant current discharges, (2) constant power discharges, (3) peak power availability, (4) stand test, and (5) simulated driving cycles. The charging method is very sensitive to battery design, so, each battery is charged according to manufacturers recommendations. The number of cycles each battery under goes during it's performance characterization is recorded, but, the usable life of the battery cannot be tested because of resource limitations.

CONSTANT CURRENT DISCHARGE - The purpose of this testing is to verify the rated capacity, show the influence of current load on capacity, and determine the batteries internal resistance. The industry standard for determining a battery's capacity is to discharge the battery at a c/3 rate (the c, in amp-hours, is given by each manufacturer). The internal resistance of a battery is a function of Depth Of Discharge (DOD) and can be calculated from a range of constant current discharges.

CONSTANT POWER DISCHARGE - The purpose of this testing is to determine the energy and coulombic capacity of the battery as a function of discharge rate (power). This plot is commonly referred to as a Ragone plot.

PEAK POWER - The purpose of this test is to measure the capability of the battery to deliver high power for up to 10 seconds at different DOD's. Ten seconds was chosen because it is more than the time required for high power demands used in the SFUDS. The test is performed by discharging the battery at a range of high currents, then the battery is discharged at a c/5 rate for five minutes and the process is repeated until the battery is fully discharged. The peak power at each DOD is calculated from the highest power found at the end of each 10 second discharge.

STAND TEST - The purpose of this test is to assess the capacity loss of the battery after an extended open-circuit period. First, the battery is fully charged and immediately discharged. Then, the battery is fully charged and open-circuited for different periods of time from 2 hours to 72 hours. These idle times where chosen because they are similar to normal driving habits. The difference between the capacity of the first test and the other tests is the capacity loss from standing.

SIMULATED DRIVING CYCLES - The purpose of this test is to predict the range of a specific electric vehicle using the test battery, on a particular driving cycle. There are several driving cycles that are regularly used to test the performance of electric vehicles, but one, the SFUDS, seems to be the most widely used. The SFUDS is based upon the federal urban driving schedule, which is the cycle on which all Internal Combustion (IC) cars derive their city fuel consumption. Figure 1 shows the SFUDS power vs. time profile. The SFUDS power spectra is derived from the U.S. Department of Energy's "Improved" Dual-Shaft Electric Propulsion (IDSEP) vehicle [2].

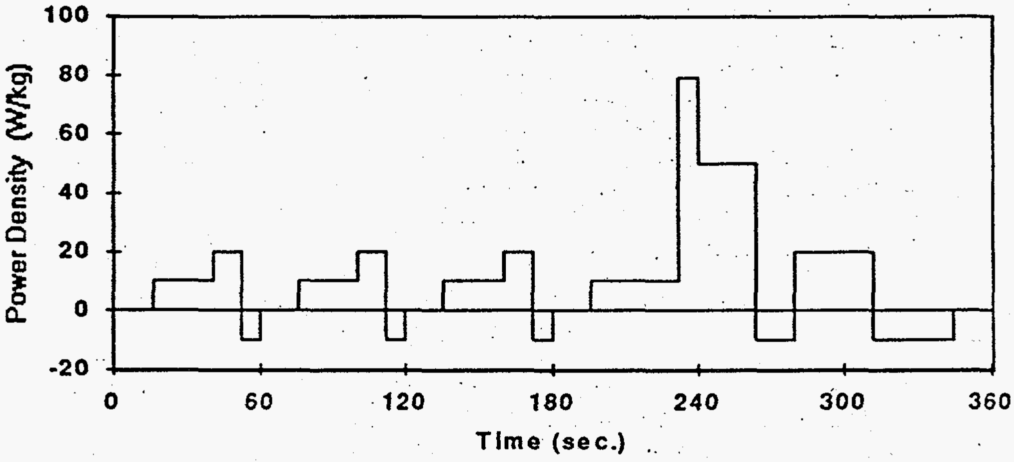

Figure 1 SFUDS battery power vs. time profile.

The IDSEP vehicle characteristics are defined below:

Curb Weight	2397 kg
Battery System Weight	695 kg
Aerodynamic Drag Coefficient	0.37
Rolling Resistance Coefficient	0.008
Frontal Area	2.97 m^2

The SFUDS cycle is approximately 3.1 km long, so, the number of cycles the battery completes times 3.1 km is the range the IDSEP vehicle will have with the test battery. The test is ended when the battery can no longer provide 50 W/kg as prescribed by the SFUDS procedure.

RESULTS AND DISCUSSION

The following subsections describes each of the eight batteries tested, the charging method used and brief description of each batteries results. Next, a table detailing the specifications and performance of each battery tested is given. Finally, two sections are used to convey the graphical and tabular results of the standard and specialized tests. The tested batteries can be divided into three groups, lead acid (four batteries), nickel positive electrode (one battery pack and 2 single cells) and a zinc bromide battery (32 cells). The nickel positive electrode batteries consisted of one nickel cadmium pack (20 cells) and two nickel metal hydride batteries. Each battery or cell was provided by a different manufacture.

Due to limited availability the tested battery are of different masses and capacities. The following bar charts graphically describe the test weight and measured battery capacity at a 3 hour rate.

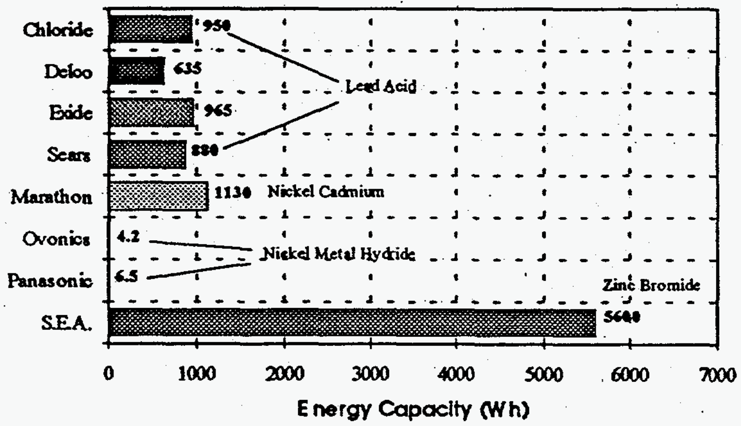

Figure 2 Nominal energy capacity of each battery tested.

The largest battery tested was the zinc bromide followed by the nickel cadmium battery pack, and the lead acid. The nickel metal hydride cells tested were very small. In interpreting the results the reader should keep in mind that there is a great difference in the different battery sizes.

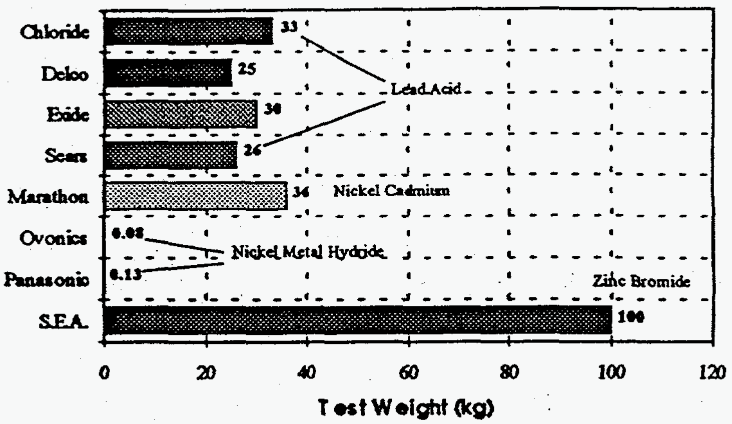

Figure 3 Weight of each battery tested.

Given an electric vehicle requirement of 15 kWh the zinc bromide battery is 1/3 full scale the nickel cadmium pack and lead acid batteries are approximately 1/15 of full scale while the nickel metal hydride batteries are approximately 1/3000 of a full scale pack.

LEAD ACID BATTERY DESCRIPTION - The four lead acid batteries tested consisted of two 3 cell modules and two 6 cell modules. All lead acid batteries were of approximately the same weight and capacity.

Flooded Lead-Acid (Chloride) - Several 6 volt, 205 Ahr modules (3ET205) manufactured by Chloride Motive Power of the United Kingdom were tested. These modules are used in many EVs including the G-Van from VEHMA. The batteries were purchased in January 1992 for use in several EVs at Texas A&M University.

A three step constant current method of 36/24/12 amps is applied till 7.2/7.5/7.9 volts is reached. Then the voltage is held constant at 7.9 volts till the current tapers to 6 amps. This allows for a 20% overcharge. Watering is required every two weeks or 15 cycles. In the G-Vans an automatic watering system is employed.

The module attained a specific energy of 29 Wh/kg (3 hr rate), but the peak power could not be tested because of the current limitations on the cyclers. This battery uses a unique tubular positive electrode that should provide longer life. One of the G-Vans used at TAMU has over 8,500 miles on it, during which 5 of the 36 batteries had to be replaced due to failures.

Sealed Lead-Acid (Delco) - Several 12 volt, 105 Ahr modules (M27MF) manufactured by Delco-Remy of the United States were tested. These modules are designed for use in marine applications. The batteries were purchased in February 1992 for use as a temporary propulsion pack for one of the Texas A&M EVs.

A three step charge method, 15 amps to 14.8 volts, hold 14.8 volts to 2 amps, 1 amp for four hours, was used that results in a 5 -10% overcharge. But, the best results were attained when a standard 12 volt taper charger was used. The battery is sealed and requires no maintenance.

The modules attained specific energies of 25 Wh/kg (3 hr rate) and a peak power of 55 W/kg at 50% DOD. The batteries require a very long charge time and the performance seemed to be degrading after only 50 deep cycles.

Flooded Lead-Acid (EXIDE) - Several 6 volt, 200 Ahr modules (GC-5) manufactured by EXIDE Motive Power of Horsham, Pennsylvania were tested. These modules are designed for golf carts and EV conversions. The batteries were purchased in August 1991 for testing and use in one of the Texas A&M EVs.

The module's charge sequence is; 25 amps to 7.65 volts, hold 7.65 volts for 3 hrs, then 4 amps for 3 hours, which provides a 20% overcharge. The batteries require watering every 15 cycles or two weeks.

The modules attained a specific energy of 32 Wh/kg (3 hr rate), but the peak power could not be tested because of the current limitations on the cyclers. The specific energy is only average, but the battery is very inexpensive. The battery pack has provided over 3,500 miles in the converted LYNX.

Flooded Lead-Acid (Sears) - One 12 volt, 115 Ahr module (96522) manufactured by Johnson Controls Inc. for Sears retail stores of the United States was tested. the battery is designed for starting and auxiliary use in marine applications. The battery was purchased in August 1992 for evaluation for use in a high speed electric vehicle.

The module requires a three step charging process; 10 amps to 14.8 volts, constant 14.8 volts to 2 amps, 1 amp for 4 hours, which provides a 20% overcharge. The batteries require watering every 15 cycles or two weeks.

The module attained a specific energy of 34 Wh/kg (3 hr rate) and had a peak power of 82 W/kg at 50% DOD. The specific energy capacity of the battery is the best of the lead-acid group, but the battery was damaged during the high power tests.

NICKEL BATTERY DESCRIPTION - The three nickel electrode batteries tested consisted of a 20 cell nickel cadmium pack and two small nickel metal hydride cells. The individual nickel metal hydride cells were much smaller then the individual nickel cadmium cells

Nickel-Cadmium (Marathon) - One 25 volt, 44 Ahr module (44SP100) and one 1.2 volt, 17 Ahr cell (17SP100) manufactured by Marathon Power Technologies Battery Products, Waco, Texas were tested. These cells are designed for aircraft auxiliary and starting purposes. They were provided for evaluation, as a possible battery for use in a hybrid Electric vehicle being constructed at University of Texas at Arlington, in May 1992.

A constant current charge method, 8.8 amps for seven hours, which provides a 40 % overcharge, was recommended by the manufacture. This high overcharge required frequent water of the batteries. Every 5 to 10 cycles distilled water was added to each cell. A lower overcharge resulted is less water use and slightly less capacity.

The 44SP100 module and 17SP100 cell attained specific energies of 35 Wh/kg and 30 Wh/kg (3 hr rate) respectively. The peak power at 50% DOD was greater than 140 W/kg. This could not be determined exactly because of the current limitations on the cyclers. The specific energy of this battery is not exceptional, but because of its high power density and low dependence on discharge rate the range provided by this battery should be very consistent. Also, this battery should provide excellent cycle life (over 1000 cycles attainable says manufacture).

Nickel-Metal Hydride (Ovonics) - Two different sets of 1.2 volt, 3.5 Ahr (C-size) cells manufactured by Ovonic Battery Company in Troy, Michigan were tested. These specific cells are designed to compete with the rechargeable Ni-Cd batteries for use in radios, toys, ect. The company has been awarded money by the United States Advanced Battery Consortium to develop these into EV size batteries. The original cells were purchased at an EV show in April 1992 and the second set was sent by Ovonics in November 1992.

A constant current charge procedure, .88 amps for 4.67 hours, which provides a 17% overcharge, was determined to be the best method. The battery is sealed and requires no maintenance.

The cells attained a specific energy of 50 Wh/kg (3 hr rate) and had a peak power capability of 102 W/kg at 50% DOD. The Specific energy and peak power of this battery is excellent, but the self discharge is high. The second set of cells sent by Ovonics had a much improved self discharge rate.

Nickel-Metal Hydride (Panasonic) - Six 1.2 volt, 1.4 Ahr cells (slightly smaller than C-cell) manufactured by Matsushita Battery Industrial Co., a division of Panasonic Industry, of Osaka, Japan were tested. The cells were sent in February 1992 for testing as a replacement for rechargeable Ni-Cd batteries. The company announced in May 1992 that they had developed the worlds first sealed nickel - metal hydride batteries for EVs. The 6 volt modules have a capacity of 130 Ahr and weigh 11 kg (approximately 70 Wh/kg).

A constant current charge method, .7 amps for 2.33 hours, which provides 17% overcharge was used. The quick charge method was used to allow for life cycle testing. The batteries are sealed and require no maintenance.

Four cells were put in series to reduce cycler resolution limitations. The cells attained a specific energy of 51 Wh/kg (3 hr rate) and had the highest peak power, 192 W/kg at 50% DOD, of all the batteries tested. The energy capacity of the battery has virtually no dependence on discharge rate and the battery provides good range on the SFUDS cycle. The battery has over 95% of its original capacity after 1000 cycles.

ZINC BROMIDE BATTERY DESCRIPTION - The zinc bromide battery is a flowing electrolyte battery that uses electrolyte storage tanks and a plastic bipolar plate construction [3]. This section briefly describes the laboratory testing of a 5 kWh zinc bromide battery and electric vehicle experience at Texas A&M University using a larger 22.5 kWh zinc bromide battery from the same manufacturer.

Table 1 Summary of specifications and performance for batteries tested during 1992 - 1993.

Chemical Couple	Pb-Acid	Pb-Acid	Pb-Acid	Pb-Acid	Ni-Cd	Ni-MH	Ni-MH	Zn-Br
Manufacture	Chloride	Delco	Exide	Sears	Marathon	Ovonics	Panasonic	S.E.A.
Model	3ET205	M27MF	GC-5	96522	44SP100	C-cell	HHR140A	ZBB-5/48
No. Cells	3	6	3	6	20	1	4	32
No. Modules	1	1	1	1	20	1	4	1
Weight (kg)								
Per Module	32.8	25	30	26	1.6	0.0832	0.0313	100
As Tested	32.8	25	30	26	36	0.0832	0.126	100
Volume (L)								
Submersed	12.054	10.47	11.21	10.62	13.4	0.024	0.0352	95.25
Box	13.2	12.23	12.63	11.68	14.7	0.0251	0.0364	113.58
Electrical Characteristics								
Nominal Voltage	6	12	6	12	25	1.2	1.2	50
Nominal Ahr	205	105	200	115	44	3.5	1.4	100
Cell Voltage (100% SOC - 0% SOC)	2.15 - 1.75	2.15 - 1.75	2.15 - 1.75	2.15 - 1.75	1.3 - 1.0	1.3 - 1.0	1.3 - 1.0	1.8 - 1.0
Charging								
Charge Method	CI/CI/CI/CV[1]	CI/CV/CI[2]	CI/CV/CI[3]	CI/CV/CI[4]	CI[5]	CI[6]	CI[7]	CI[8]
Charge Time (hrs)	8 - 10	8 - 12	8 - 10	8 - 10	7	4	2	4- 6
Overcharge (%)	15 - 20	5 - 10	15 - 20	15 - 20	40	17	15 - 17	10 - 15
C/3 Capacity								
Ahr	164	54.5	164	75.9	46.3	3.58	1.31	117.4
Whr	950	635	965	879	1133	4.20	6.47	5600
Sp. Energy (Wh/kg)	29	25	32	33	35	50	51	56
Vol. Energy (Wh/L)	78.8	60.0	86.1	82.8	84.6	174.8	183.8	58.8
Efficiency								
Energy (%)	70	84	80	85	65	74	70	64
Coulomb (%)	78	97	86	90	75	88	80	87
Peak Power, (W/kg) (at 50% DOD)	***	55	***	82	> 138	102	197	56
Approximate Cycles to Date	>50	>50	>50	>50	>75	>50	>1000	>75

[1] Chloride ET-205 charge sequence, 36 amps to 7.2 volts, 24 amps to 7.5 volts, 12 amps to 7.9 volts, 7.9 volts to 6 amps.

[2] Delco 105 marine charge sequence, 15 amps to 14.8 volts, 14.8 volts to 2 amps, 1 amp for 4 hr.

[3] Exide GC-5 charge sequence, 25 amps to 7.65 volts, 7.65 volts for 3 hr, 4 amps for 3 hr.

[4] Sears Die Hard charge sequence, 10 amps to 14.8 volts, 14.8 volts to 2 amps, 1 amp for 4 hr.

[5] Marathon 44SP100 charge sequence, 8.8 amps for 7 hr.

[6] Ovonics charge sequence, 1.75 amps for 2.33 hr.

[7] Panasonic HHR140A charge sequence, .7 amps for 2.33 hrs.

[8] S.E.A. Zn-Br charge sequence, 25 amps to 64 volts.

Zinc-Bromide (S.E.A.) - Two 5 kWh, 50 volt batteries and three 22.5 kWh, 120 volt batteries manufactured by Studiengesellschaft fur Energiespeicher und Antriebssysteme, S.E.A. of Austria were tested. S.E.A. bought the rights to the technology, along with three other companies, from Exxon in 1982. S.E.A. has concentrated on EV applications while the others seem to be directing their research towards utility load leveling. The first 5 kWh battery arrived in July 1991 for lab testing and a 22.5 kWh battery arrived in January 1992. The larger batteries were constructed to fit into an existing Texas A&M University EV.

A constant current charge method, 25 to 30 amps to 64 volts for the 5 kWh, and 50 to 60 amps to 144 volts for the 22.5 kWh, was recommended by S.E.A. This method provides a 10-15% overcharge, but a higher capacity can be attained with a higher overcharge. The only maintenance is stripping (described later) every 10 cycles and monthly pH monitoring.

The 5 kWh module attained a specific energy of 56 Wh/kg (3 hr rate) and a peak power of 56 W/kg at 50% DOD. In March 1993 the 5 kWh battery suddenly had a great increase in electrolyte pH level (normally 2 to 3 increasing to 4+) and testing was stopped at approximately the 75th cycle. Energy and power characteristics provided in Table 2 and Figures 5 and 6 were measured before the pH increased. Self discharge rate was not determined due to the short test cycle. It is anticipated that the reason for the pH increase will be determined soon and battery testing will resume in July 1993.

Zinc Bromide Electric Vehicle Experience - In 1992 a 22.5 kWh battery was installed into a 1982 GM-Opel with a compound wound DC motor. The Texas A&M car completed approximate 1500 km in testing and was able to travel 175 km under normal traffic conditions from College Station to Austin, Texas on one charge. In February of 1993 a second 22.5 kWh battery was installed in a Geo Metro ("T-Star") with a 3 phase AC induction motor. The T Star was tested at the Chrysler Proving Grounds in Phoenix, Arizona and completed 189 km in two hours and was able to travel an additional 48 km before the speeds were below 50 km/hr. This same car was entered in the 1993 American Tour de Sol during the last week in May. The vehicle completed 1134 km during the week long competition, with a one day (single charge) total of 246 km. The vehicle came in second place out of a field of 39 cars. The zinc bromide powered T-Star has now reliably completed approximately 2500 km. The zinc bromide battery is typically recharged in 5 hours and consistently provides greater then 160 km in normal traffic conditions.

STANDARD TEST RESULTS

Table 1 lists the various battery specifications including cell arrangement, weight, volume, charging method, capacity and efficiency of each battery technology evaluated at Texas A&M University during 1992 - 1993. Figures 2 and 3 graphically show the relative energy capacities and weights of the batteries listed in Table 1. Figure 4 shows the normalized Peukert curves for several of the batteries tested at Texas A&M University. This normalizing procedure allows batteries of different sizes and chemistries to be easily compared. This figure demonstrates the effect of discharge rate on the coulombic capacity of the selected batteries. A good battery is one that is independent of discharge rate and will show up on the graph as a horizontal line. The nickel based batteries, which closely attain their rated capacity at all rates of discharge, tend to be independent of discharge rate, while the lead based batteries, which are more so affected by the rate of discharge, tend to be dependent on discharge rate.

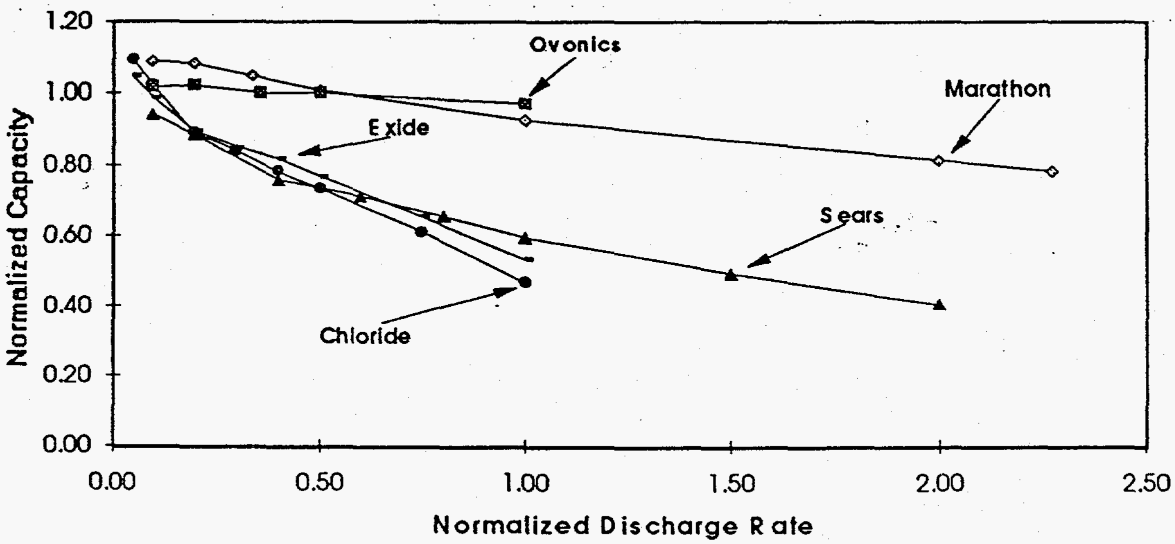

Figure 4 Peukert curves, shows effect of discharge current on the available coulombic capacity of several battery technologies tested at TAMU. Normalized capacity is equal to capacity divided by c-rating of each battery. Normalized discharge rate is equal to actual discharge rate divided by c-rating of each battery.

A composite plot, called a Ragone plot, comparing the effect of constant power discharges on the different battery technologies energy capacity is shown in Figure 5. The ideal battery, as presented on a Ragone plot, would have a very high specific energy capacity with no dependence on discharge rate. This would be a horizontal line on the Ragone plot. The S.E.A. Zn-Br battery has a very high energy density at lower rates of discharge, but is seen to be very strongly influenced by discharge rate. The Pb-Acids have a lower overall energy density and show a similar dependency on discharge rate, but to a lesser extent than the Zn-Br battery. Both the nickel based batteries demonstrate an almost independent relationship with discharge rate, but the Panasonic Ni-MH shows an overall greater specific energy. The Ovonics battery could not be tested in the lower specific power ranges because of cycler resolution limitations. The plot of specific peak power as a function of DOD is shown in Figure 6. An ideal EV battery would provide peak power with no dependence on DOD, this would be a horizontal line on the graph. In this plot the Nickel based batteries faired much better than either the Pb-Acids or the Zn-Br. The Panasonic battery showed exceptional power density with little dependence on DOD.

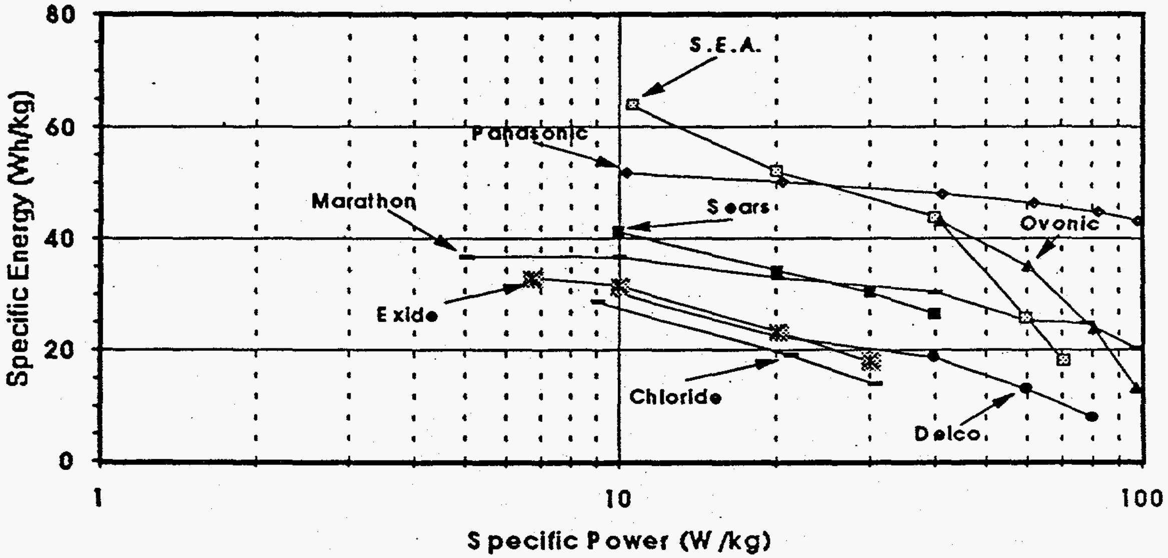

Figure 5 Ragone plot, shows effect of discharge rate (specific power) on the available energy capacity (specific energy) of the eight advanced battery technologies.

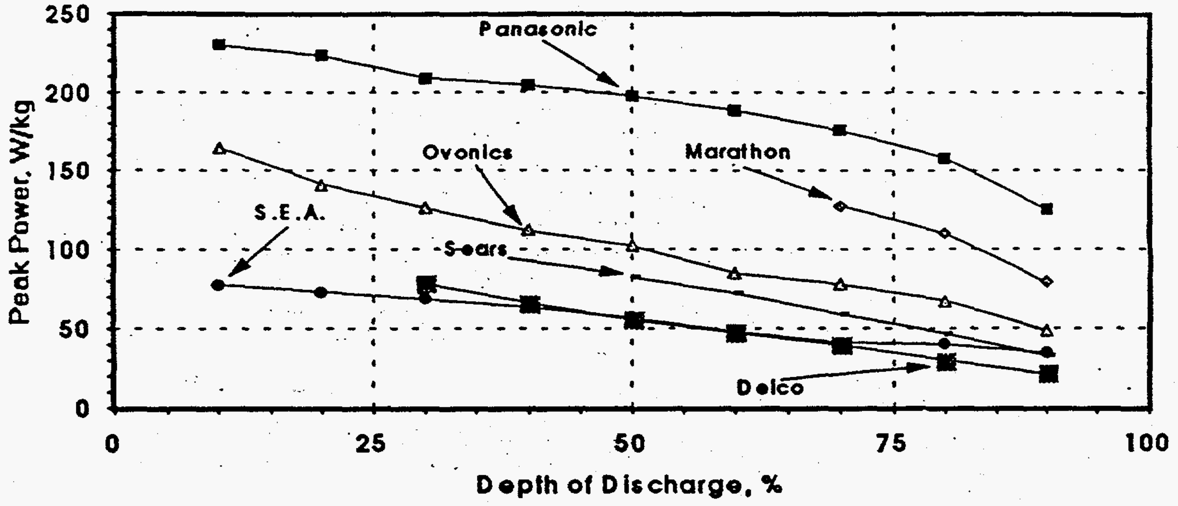

Figure 6 Peak power plot, shows effect of DOD on the available peak power of several of the advanced battery technologies.

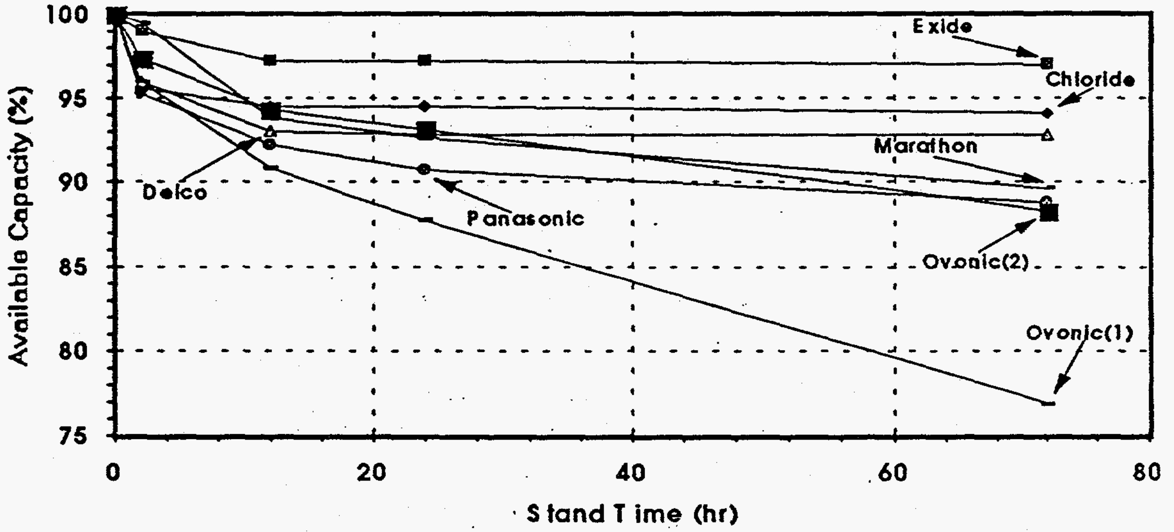

Figure 7 Self-discharge plot, shows effect of stand time on the available capacity of several advanced battery technologies. Ovonic(1): Original battery sent for testing, Ovonic(2): improved battery sent for testing.

The Marathon Ni-Cd was expected to demonstrate similar capabilities, but the peak power could not be derived at the higher SOC due to the current limitations of the cyclers. Several of the Pb-Acids could not be tested at all due to this current limitation. The S.E.A. battery is seen to have a low overall power density.

When an EV is left charged or partially charged over a period of time the self discharge of the batteries becomes important. Figure 7 demonstrates the self-discharge that occurs for several advanced batteries. The Pb-Acid batteries show an initial loss in capacity in the first 12 hours of stand time, but there is virtually no further capacity loss after this time. The flooded Pb-Acid batteries faired better than the sealed one. All the Nickel based batteries exhibit relatively high self discharge when compared to the Pb-Acid type. After three days they have lost over 10% of their original capacity. The original Ovonics battery had a very high self discharge, almost double that of other Nickel based batteries, but the second one was much better. The Zn-Br battery should theoretically have very little self discharge since its reactants are stored in separate areas of the battery, but, in practice the self discharge is as high or higher than some of the other chemistries tested. The Zn-Br battery could not be plotted because the batteries pH suddenly increased during its self discharge test.

Some of the batteries have been tested under simulated driving profiles. The results of these tests are tabulated in Table 2. Most of the batteries could not be tested because of cycler power or resolution limitations. A future project will be to determine a driving cycle that is within the power capabilities of the cyclers for all the battery technologies being tested. The Ni-MH batteries provided a better range on the SFUDS, with the Panasonic battery going the farthest.

Also, in Table 2 are the results of comparison of the range of the Marathon Ni-Cd batteries with and without regeneration during the SFUDS cycle. The results show that the range of the IDSEP van was significantly increased with regeneration. The increase in range is a result of the battery having near perfect coulombic efficiency during regeneration.

Table 2 Ranges of advanced batteries derived from simulated driving cycles.

Driving Schedule Characteristics	
Driving Cycle	SFUDS
Vehicle Type/Model	Van/IDSEP
Battery Weight (kg)	695
Average Speed (kph)	30.6
Peak Power (w/kg)	79
Average Power (w/kg)	10
Battery Type/Model	Range (km)
Ni-MH / Panasonic	138
Ni-MH / Ovonics	110
Ni-Cd / Marathon	90
Effect of regeneration on Marathon Ni-Cd	
Cycle Type	Range (km)
SFUDS w/regeneration	90
SFUDS w/o/regeneration	78

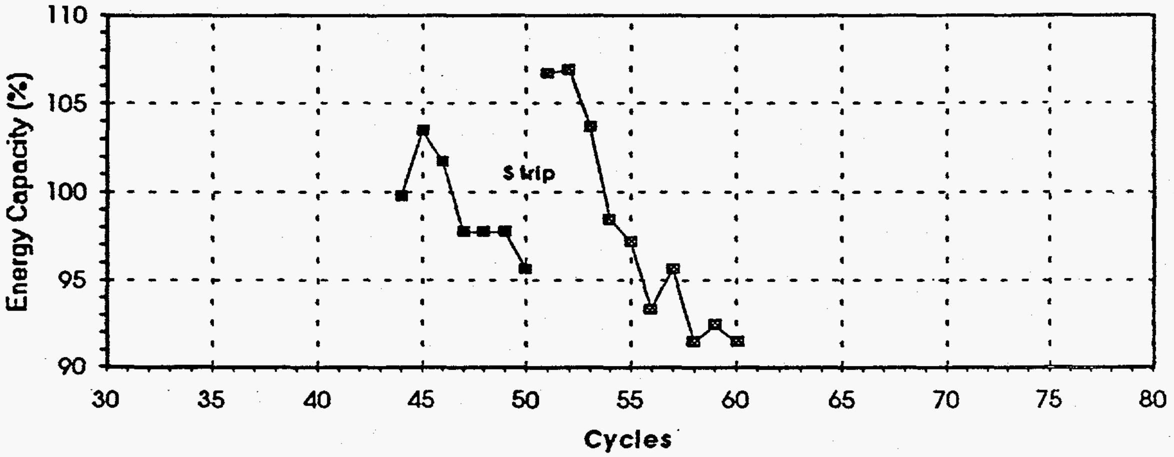

Figure 7 Zinc-bromide energy capacity loss as a function of cycles between stripping.

SPECIALIZED TEST RESULTS

A Zn-Br battery requires a maintenance procedure called stripping every 10 or more cycles. The stripping procedure requires that the battery be deep discharged, then short circuited. The battery is left short circuited with the pumps running for 8 to 12 hours. This maintenance procedure cleans the electrode surface of unwanted Zinc and prevents Zinc dendrites from penetrated the separator. Figure 7 shows that the Zn-Br battery provides its best energy capacity on the second cycle after a strip and provides more than its rated nominal capacity for the first three cycles after a strip. A well designed charger could be made that has the capability to charge and strip the battery, also it could take the energy during stripping and return it to the grid.

APPLICATIONS OF DATA

The following paragraphs describe several methods for estimating the range of the IDSEP van, however, these methods will work well for any EV. The first method uses the Ragone plot and works well for constant speed ranges and the second method utilizes the peak power plot and can be used for any driving cycle. Finally, battery cost limitations are imposed and the range is derived.

The range of the IDSEP van can be estimated from the Ragone plot if the power vs. speed relationship for the vehicle is known. Since the IDSEP van uses 7 kW at 55 kph and the battery weighs 695 kg, then the specific power required of the battery will be approximately 10 w/kg. Moving vertically from the 10 w/kg point on the abscissa or horizontal axis until the desired battery line is intercepted and then moving horizontally left from the interception point to the ordinate or vertical axis gives the available specific energy. Dividing the specific energy by the specific power results in the discharge time. Multiplying the discharge time by the speed of the vehicle results in the range.

Table 4 shows the range provided by some of the advanced EV batteries using the example above. The table indicates that the vehicle range is a simple function of battery energy density and vehicle energy use (127 Wh/km). A very high energy density battery like the zinc bromide results in a longer range. However, vehicles seldom travel at constant speed, during any particular driving cycle the peak power requirement can be considerably higher than the average.

Hornstra [4] has shown that the range of a particular vehicle on a given driving cycles can be determined by knowing the average and peak power of the cycle. The average specific power required of the battery can be calculated from the average power and battery mass. The energy capacity of the battery at this rate can be determined from the Ragone plot. Furthermore, the battery's discharge time and vehicle range can be found. But, the vehicle will fail the driving schedule earlier than predicted by the Ragone plot because of peak power requirements placed on the battery.

Table 4 Estimated Range of the IDSEP van derived from the Ragone plot (Figure 5). The van uses 7 kW at 55 kph with a 695 kg battery pack.

EV Battery	Specific Energy (Wh/kg)	Discharge Time (hr)	Range (km)
Marathon	35	3.5	192
Panasonic	50	5.0	275
Sears	41	4.1	225
S.E.A.	64	6.4	352

Table 5 Predicted range of IDSEP van on the SFUDS using the method described above (average speed = 30.6 kph).

EV Battery	Specific Energy (Wh/kg)	Usable DOD (%)	Discharge Time (hr)	Range (km)
Marathon	35	95	3.32	101
Panasonic	50	98	4.90	150
Sears	41	80	3.28	100
S.E.A.	64	60	3.84	117

Applying this requirement to the peak power plot, the DOD at which the battery will fail the driving schedule is determined. The fraction of the DOD multiplied by the battery discharge time derived from the Ragone plot will give the discharge time. With a Ragone and peak power plot, the range of any EV on a driving cycle can be approximated.

Utilizing Hornstra's method the SFUDS range for the four battery presented in Table 4 is calculated and presented in Table 5. Comparing Table 5 approximate results with the Table 2 experimentally simulated ranges shows that the predicted ranges over estimate by 8.5 % for the Panasonic Ni-MH and 12 % for the Marathon Ni-Cd.

The Table 5 predicted ranges under the dynamic SFUDS case are substantially less then the steady speed case presented in Table 4. This is due to the much higher energy use, 227 Wh/km and the fact that the usable DOD is less then 100%. The most dramatic range reduction occurred for the zinc bromide case which was limited to a usable DOD of 60%. In contrast the nickel metal hydride battery had a usable DOD of 98%. This indicates the need for a power peaking device such as an ultra capacitor. Given power peaking the DOD of the zinc bromide could be extended to approximately 90% resulting in a predicted range of 176 km. There would be no range gain by incorporating power peaking with the nickel metal hydride battery.

The above analysis of vehicle range as a function of load and does not take into consideration many other important properties such as initial cost, life, and recyclability.

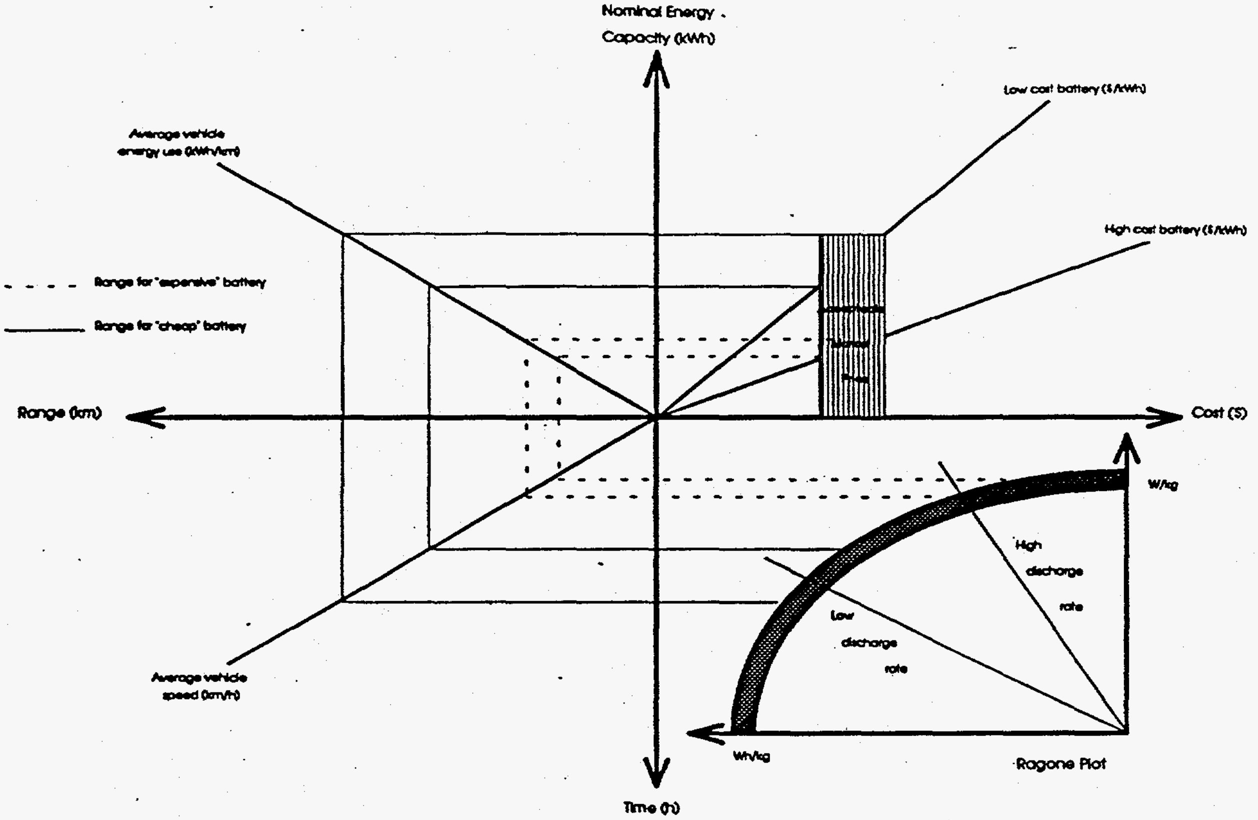

Figure 8 Diagram showing relationship between cost, range and the Ragone plot.

The relationship between battery cost and EV range is schematically represented in Figure 8 [5]. The diagram starts in the upper right quadrant with an acceptable market price range for EV batteries. If the battery is cheap, then more energy capacity can be purchased than if it is expensive. For example more kWh of low cost lead batteries can be purchased then nickel cadmium. The range of the vehicle can be determined from the average energy consumption of the vehicle and the discharge rate of the battery. Generally low cost batteries have low values on the Ragone plot. However a larger mass of battery can be purchase and therefore the average electrical load W/kg is less. The mass of battery that the vehicle can carry is limited.

For example consider an electric van with an acceptable battery cost of $5000 and a maximum battery weight of 450 kg. For an expensive battery such as the nickel cadmium the limitation becomes cost. Using an estimated mass production cost of $700/kWh [6] the $5000 will only buy 7.1 kWh, with an approximate weight of 203 kg. For a zinc bromide battery (estimated mass produced cost of $250/kWh [5]) $5000 will buy 20 kWh at an approximate weight of 357 kg. For a sealed electric vehicle lead acid battery (estimated mass produced cost of $200/kWh) $5000 will buy 25 kWh but the weight is 833 kg. In the lead acid case the limitation is weight. At a maximum of 450 kg the lead acid can provide 13.5 kWh (30 Wh/kg) at cost of $2700.

In this analysis the nickel cadmium provides the least range for an acceptable battery cost. The zinc bromide provides the longest range and increased payload by weighing less than the maximum battery weight. The lead acid battery is weight limited and provides a range between the other two batteries at a lower cost. Note that this analysis only considers initial cost rather then life cycle cost for the technologies.

SUMMARY

This paper presented the results of tests performed on four different battery technologies. Five standardized tests and several specialized tests were used to characterize and compare the different battery technologies. The results were summarized in graphical and tabular formats. Several methods were presented on determining the expected ranges of battery powered EVs.

CONCLUSIONS

The four battery technologies have individual strengths and weaknesses and each may be suited to fill a particular application. The lead acid batteries have a low specific energy and moderate power density, but they are cheap and can be easily recycled. This battery is applicable to inexpensive, short range cars and perhaps to larger vans that can accept a heavy battery pack. The sealed lead acid batteries have similar performance characteristics and applications to the flooded ones but they have the advantage of being maintenance free.

The tested nickel cadmium battery had a specific energy density slightly greater then lead acid, good power density and an anticipated long cycle life. The nickel metal hydride batteries have even better performance characteristics. However the nickel electrode used in both of these battery is costly. These batteries may best fill the needs of peaking devices in hybrid and high power EV applications.

The zinc bromide battery has high specific energy, low power density and an anticipated long cycle life. The battery requires a control system for operation and will probably need to be hybridized with a power peaking device to meet consumer acceleration expectations. The battery uses inexpensive raw materials and is flexible in design. This battery is probably best suited for EVs where minimum battery weight and long range is important i.e. commuter cars.

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1. Hornstra, F., and Yao, N., "Standard Test Procedures for Electric Vehicle Batteries at the National Battery Test Laboratory", SAE Paper No. 820401.

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3. Tomazic, G. S., " The Zinc Bromide Battery Development by S.E.A.", The 11th International Electric Vehicle Symposium, Florence, Italy, September 27 - 30, 1992.

4. Hornstra, F., "A Methodology to Assess the Impact of Driving Schedules and Drive Train Characteristics on Electric Vehicle Range", Argonne National Laboratory.

5. Tomazic, G., "Considerations Regarding the Comparison of Traction Batteries", Essen, March 2, 1993.

6. Burke, A. F., "Battery Availability for Near Term (1998) Electric Vehicles", SAE Paper No. 911914.

OTHER SOURCES CONSULTED

Bitrode Cycle Life Tester Software User Manual and Hardware Operation Manual

DeLuca W. H. et al., "Performance Evaluation of Advanced Battery Technologies for Electric Vehicle Applications", Proceedings of 25th Intersociety Energy Conversion Engineering Conference, Reno, NV, August 12 - 17, 1990, Vol. 3, pp. 314 - 319.

DeLuca W. H. et al., "Performance and Life Evaluation of Advanced Battery Technologies for Electric Vehicle Applications", SAE paper No. 911634.

Comparison of Various Battery Technologies for Electric Vehicles

Blake E. Dickinson

Talk Outline

- Introduction
  - Background
  - Objective
- Procedure
- Results
- Applications of Data
- Summary/Conclusions

Tasks required to Fulfill Objective

- Identification of a standard set of testing procedures for electric vehicle batteries based on industry accepted testing procedures, and tests which are specific to individual battery types from the literature.
- Determination of the limitations of the available testing equipment.
- Evaluation of batteries by conducting performance tests, and by subjecting them to cyclical loading, using a computer controlled charge - discharge cycler, to simulate typical EV driving cycles.
- Summarized results, battery characterization, performance and comparison data, in plots and tables.
- Comparison of the batteries based on: performance, projected vehicle range, cost, and applicability to various types of EVs.

Experimental Apparatus - Batteries

- Eight Batteries
- Four Technologies
  - Lead-Acid
  - Nickel-Cadmium
  - Nickel-Metal Hydride
  - Zinc-Bromide

Experimental Apparatus - Cycler Specifications

Module #	Voltage (volts) / Accuracy	Current (amps) / Accuracy	Power (watts) / Accuracy	Temp. (^{O} C) / Accuracy	Data Storage
1 & 2	0 - 18 ± 0.0005	± 50 ± 0.005	900 ± 0.05	0 - 200 ± 1	120 lines
3	0 - 54 ± 0.005	± 100 ± 0.05	5400 ± 0.5	0 - 200 ± 1	120 lines
4	0 - 160 ± 0.05	± 200 ± 0.5	32000 ± 50	0 - 200 ± 1	240 lines

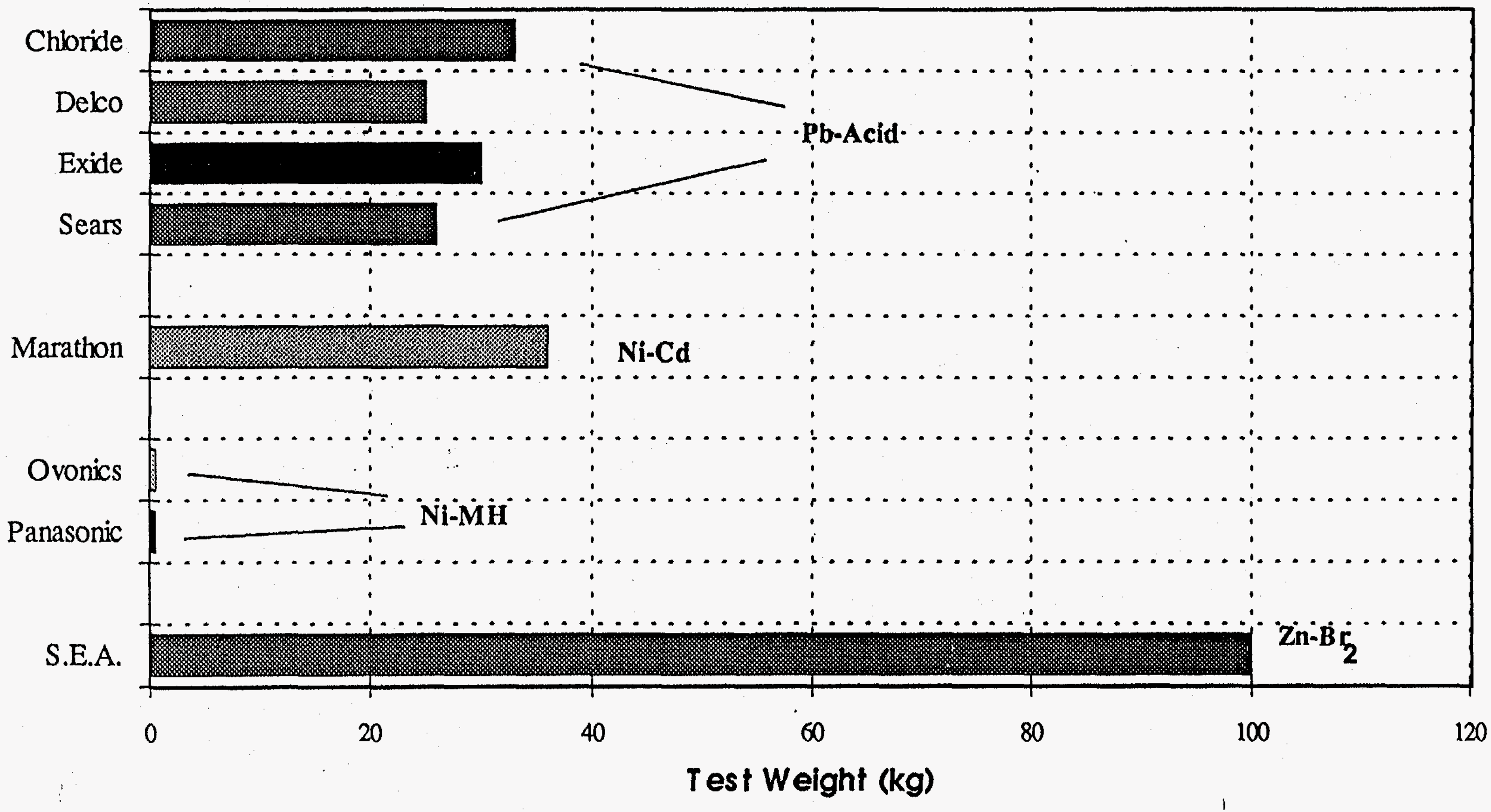
Procedure

- Performance Tests
  - Constant Current (Peukert Curves)
  - Constant Power (Ragone Plot)
  - Peak Power
  - Self Discharge
  - Driving Cycle Performance

Test Matrix

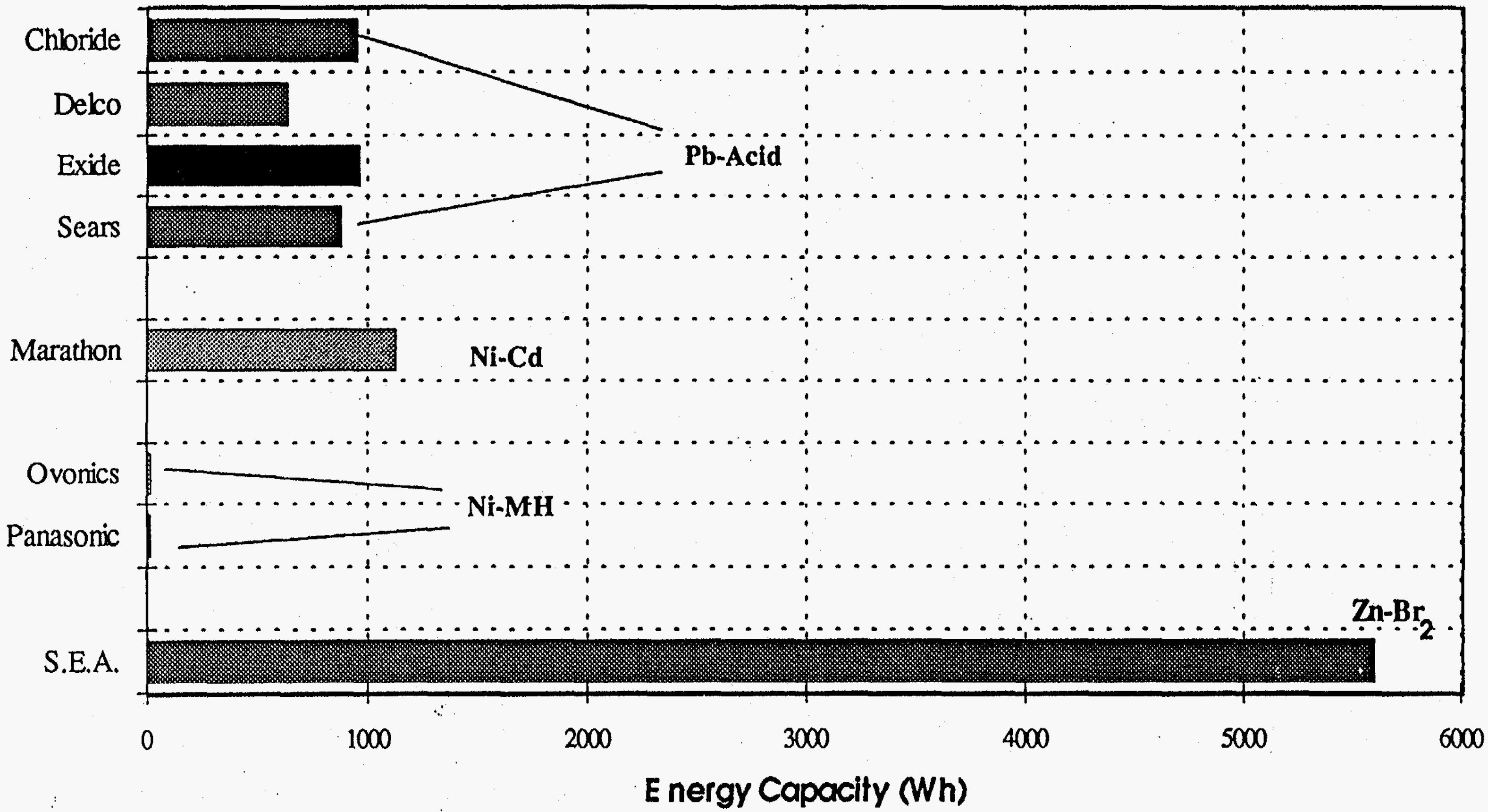
Battery	Constant Current	Ragone Plot	Peak Power	Self Discharge	Simulated Driving Cycle
Chloride	X	X		X	
Delco	X	X	X	X	
Exide	X	X		X	
Sears	X	X	X		
Marathon	X	X	X	X	X
Ovonics	X	X	X	X	X
Panasonic	X	X	X	X	X
S.E.A.	X	X	X		

Battery Weight



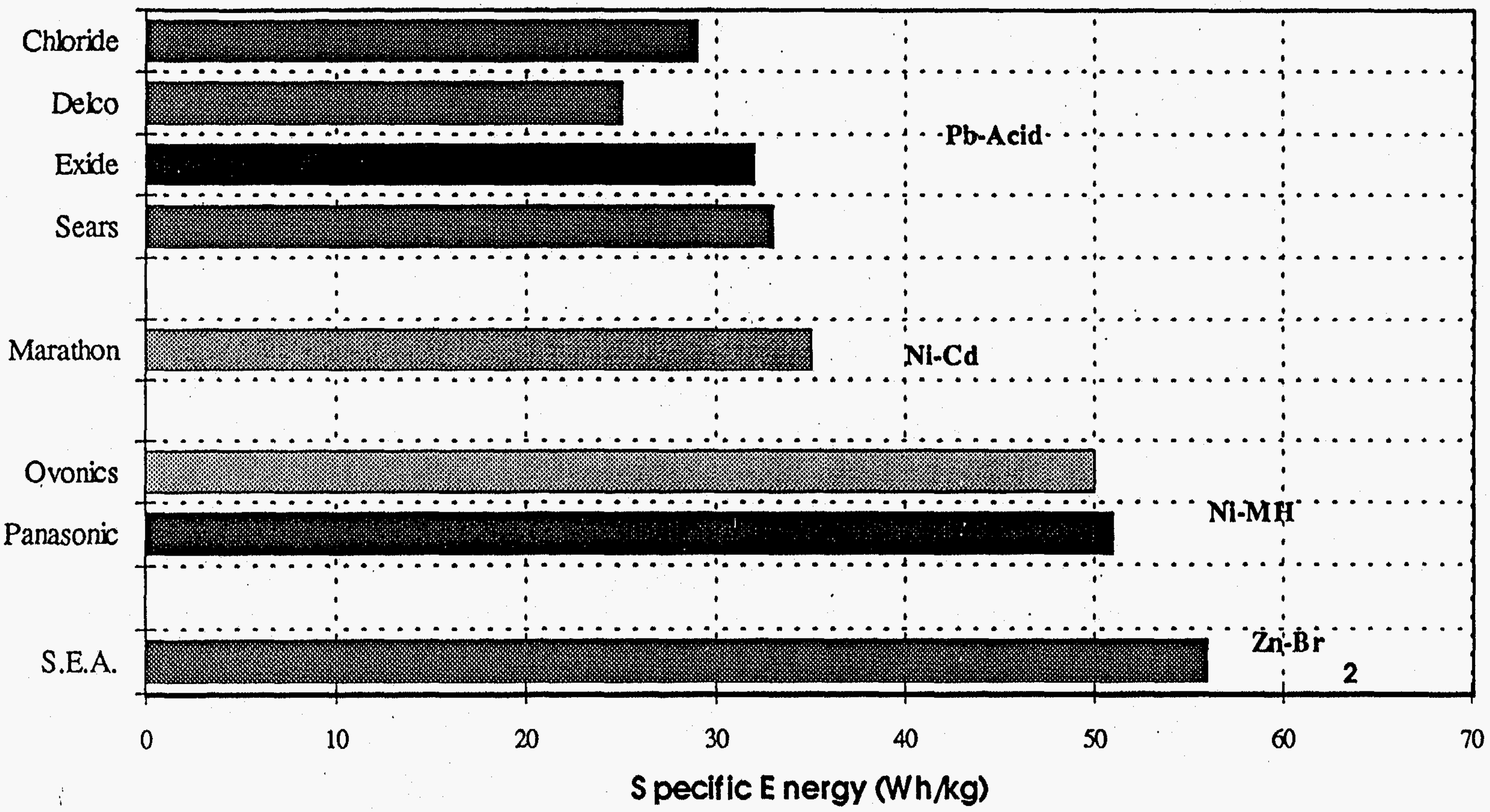
Pb-Acid Ni-Cd Ni-MH Zn-Br_2

Battery Energy Capacity (c/3 rate)



Pb-Acid Ni-Cd Ni-MH Zn-Br$_2$

Battery Specific Energy (c/3 rate)

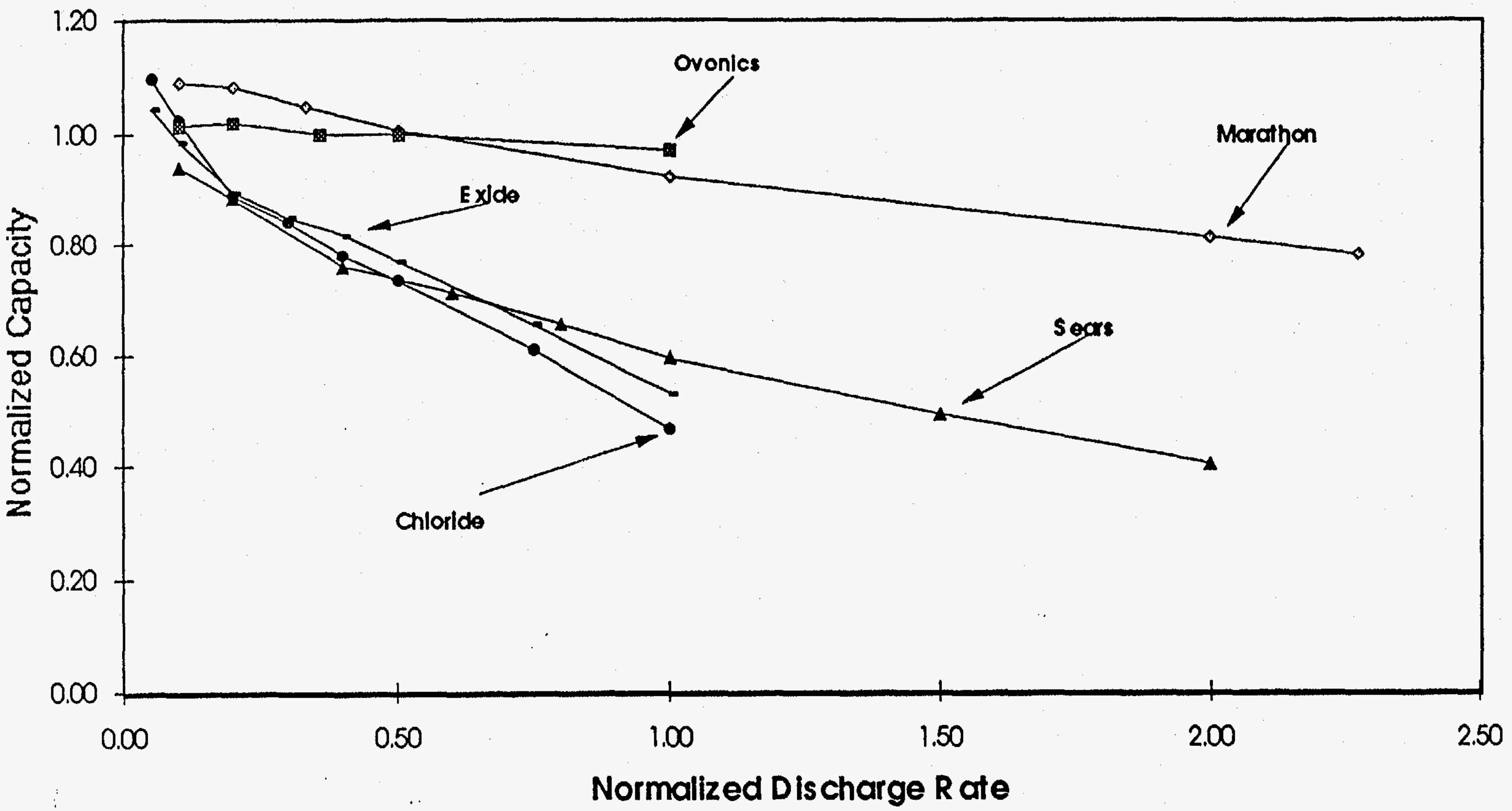


Pb-Acid Ni-Cd Ni-MH Zn-Br_2

Summary of Battery's Specifications and Performance

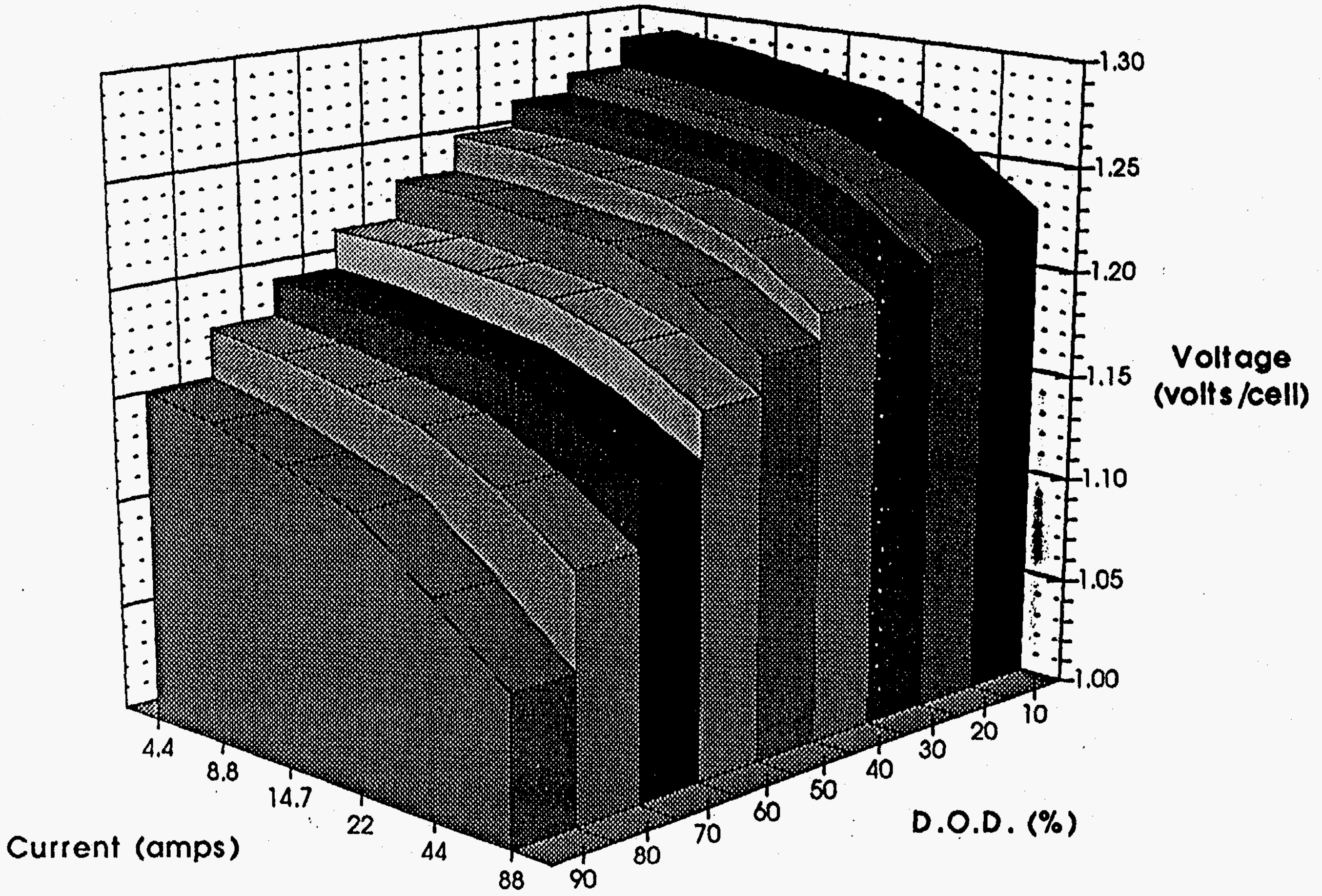
Chemical Couple	Pb-Acid	Pb-Acid	Pb-Acid	Pb-Acid	Ni-Cd	Ni-MH	Ni-MH	Zn-Br
Manufacture	Chloride	Delco	Exide	Sears	Marathon	Ovonics	Panasonic	S.E.A.
Model	3ET205	M27MF	GC-5	96522	44SP100	C-cell	HHR140A	ZBB-5/48
No. Cells	3	6	3	6	20	1	4	32
No. Modules	1	1	1	1	20	1	4	1
Weight (kg)								
Per Module	32.8	25	30	26	1.6	0.0832	0.0313	100
As Tested	32.8	25	30	26	36	0.0832	0.126	100
Volume (L)								
Submersed	12.054	10.47	11.21	10.62	13.4	0.024	0.0352	95.25
Box	13.2	12.23	12.63	11.68	14.7	0.0251	0.0364	113.58
Electrical Characteristics								
Nominal Voltage	6	12	6	12	25	1.2	1.2	50
Nominal Ahr	205	105	200	115	44	3.5	1.4	100
Cell Voltage (100% SOC - 0% SOC)	2.15 - 1.75	2.15 - 1.75	2.15 - 1.75	2.15 - 1.75	1.3 - 1.0	1.3 - 1.0	1.3 - 1.0	1.8 - 1.0
Charging								
Charge Method	CI/CI/CI/CV[1]	CI/CV/CI[2]	CI/CV/CI[3]	CI/CV/CI[4]	CI[5]	CI[6]	CI[7]	CI[8]
Charge Time (hrs)	8 - 10	8 - 12	8 - 10	8 - 10	7	4	2	4 - 6
Overcharge (%)	15 - 20	5 - 10	15 - 20	15 - 20	40	17	15 - 17	10 - 15
C/3 Capacity								
Ahr	164	54.5	164	75.9	46.3	3.58	1.31	117.4
Whr	950	635	965	879	1133	4.20	6.47	5600
Sp. Energy (Wh/kg)	29	25	32	33	35	50	51	56
Vol. Energy (Wh/L)	78.8	60.0	86.1	82.8	84.6	174.8	183.8	58.8
Efficiency								
Energy (%)	70	84	80	85	65	74	70	64
Coulomb (%)	78	97	86	90	75	88	80	87
Peak Power, (W/kg) (at 50% DOD)	***	55	***	82	> 138	102	197	56
Approximate Cycles to Date	>50	>50	>50	>50	>75	>50	>1000	>75

Normalized Peukert Curves

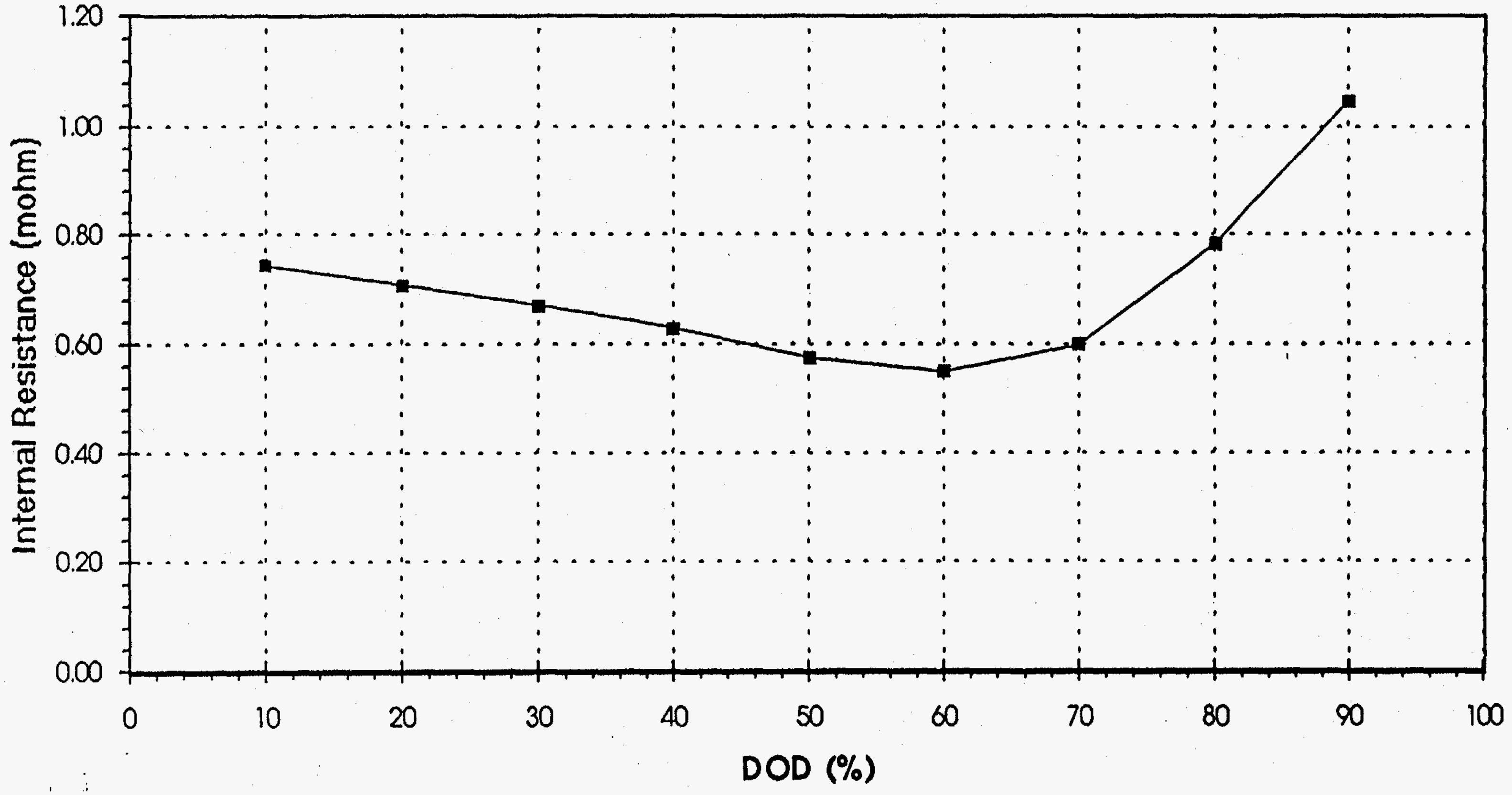


Pb-Acid Ni-Cd Ni-MH Zn-Br_2

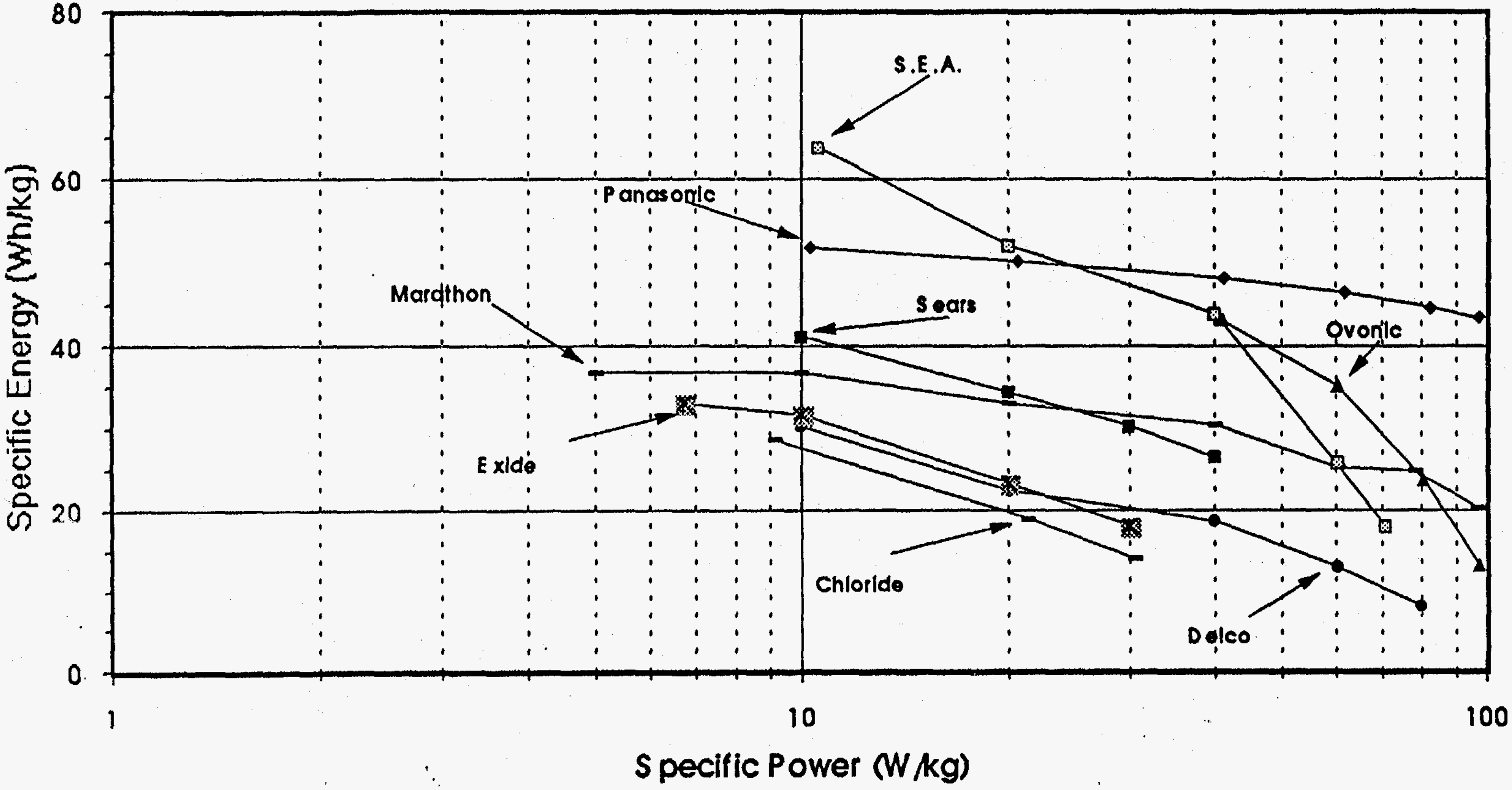
Voltage Map of Marathon Ni-Cd



Internal Resistance of Marathon Ni-Cd

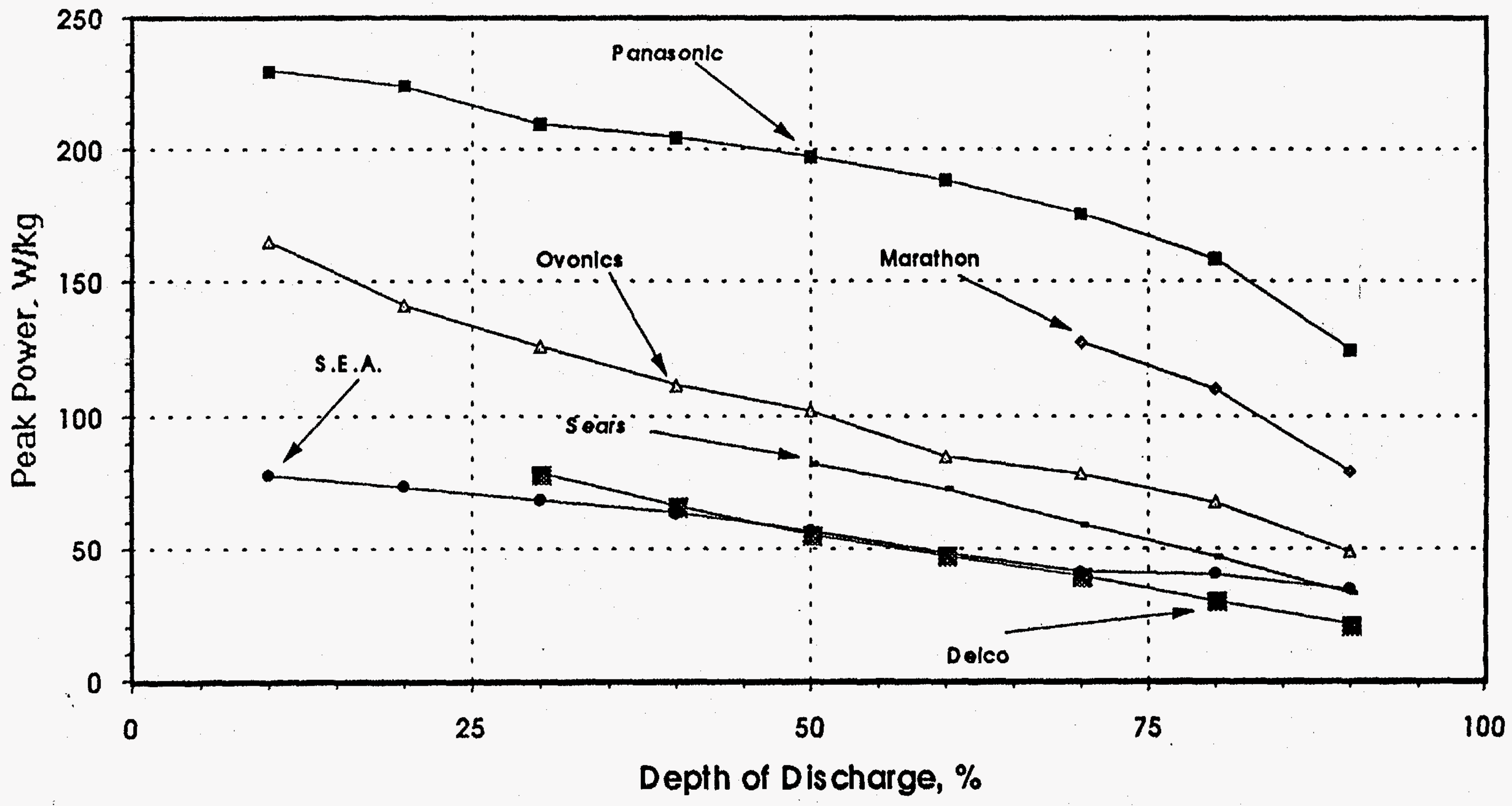


Ragone Plot



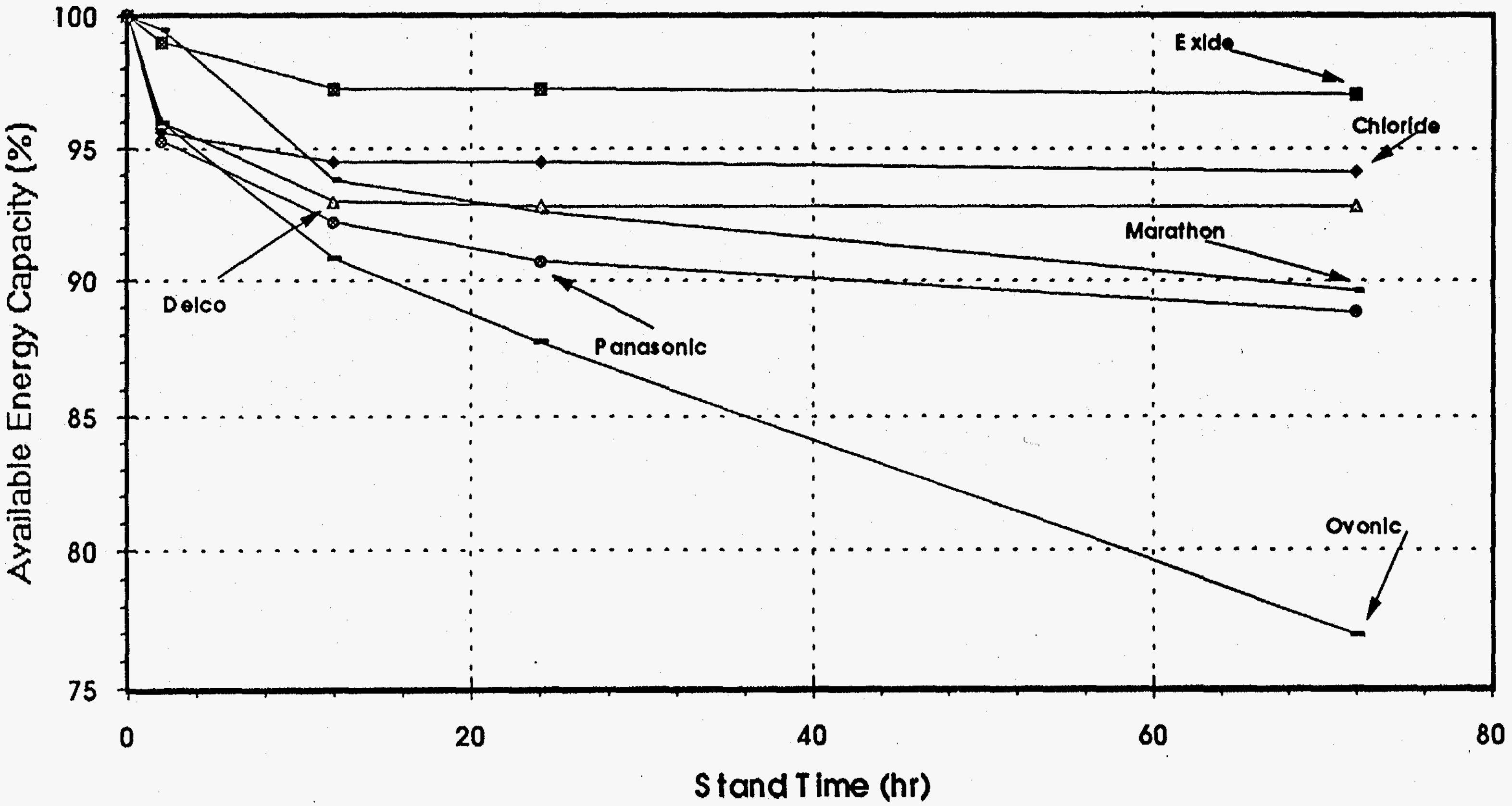
Pb-Acid Ni-Cd Ni-MH $Zn-Br_2$

Peak Power Plot



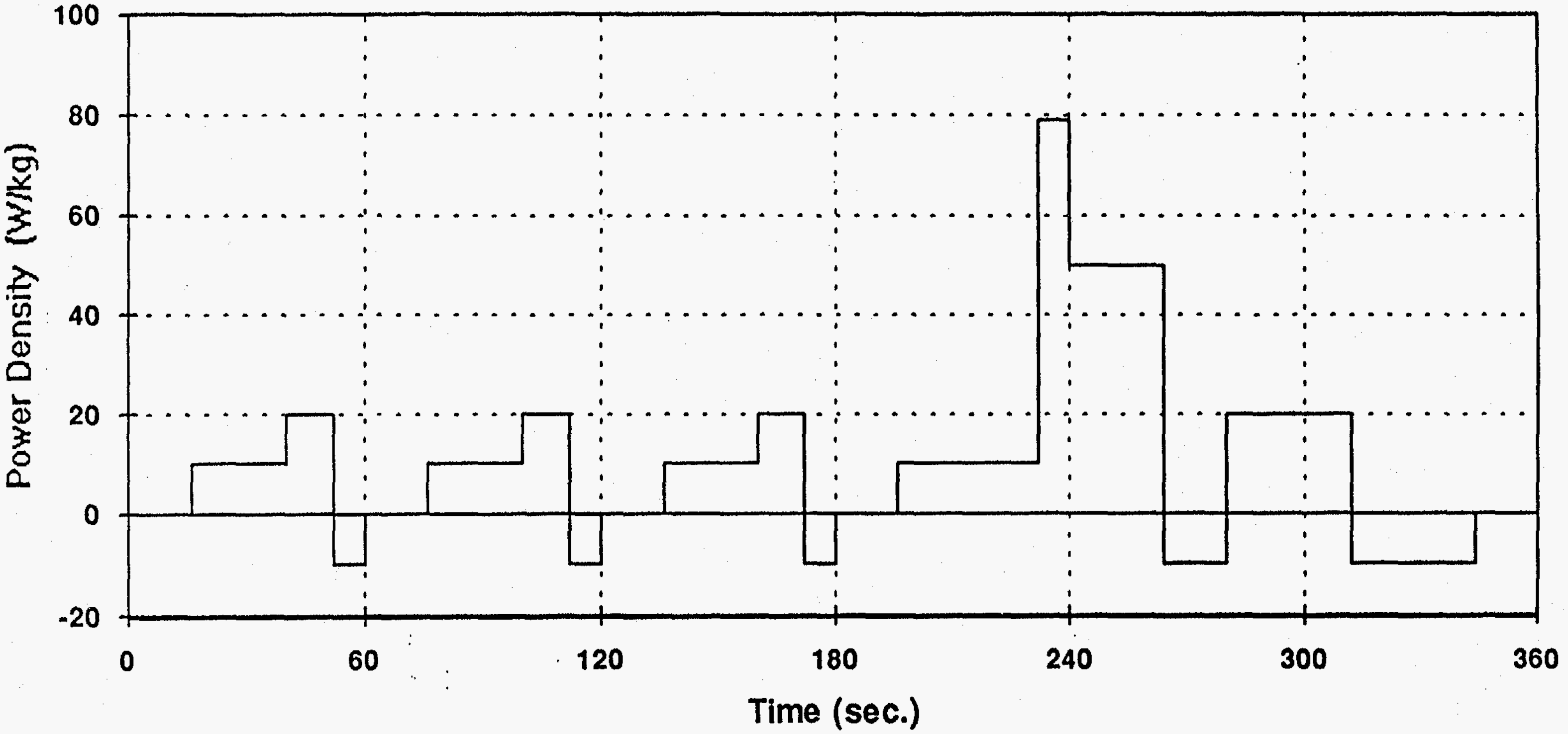
Pb-Acid Ni-Cd Ni-MH Zn-Br_2

Self Discharge Plot



Pb-Acid Ni-Cd Ni-MH Zn-Br_2

Simplified Federal Urban Driving Schedule



Vehicle: IDSEP van Battery Weight: 695 kg Avg Speed: 30.6 kph

Average Power: 10 W/kg Peak Power: 79 W/kg

Ranges of Batteries on Simulated SFUDS

Battery Type/Model	Range (km)
Ni-MH / Panasonic	138
Ni-MH / Ovonics	110
Ni-Cd / Marathon	90
Effect of regeneration on Marathon Ni-Cd	
Cycle Type	Range (km)
SFUDS w/regeneration	90
SFUDS w/o/regeneration	78

Regen Efficiency and Range Increase

Batteries	Cycle
Ni-Cd	SFUDS w & w/o regen
Pb-Acid	SFUDS w & w/o regen

≈ 15% increase in range

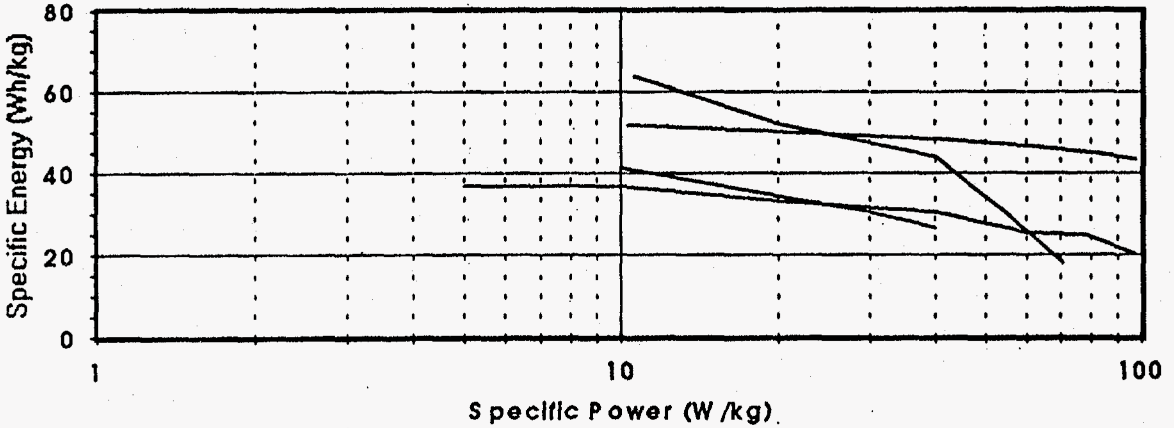
- Efficiency of Regen

  ≈ 100% Colombic

  ≈ 90% Energy

Range of IDSEP van at Constant 55 kph Speed

EV Battery	Specific Energy (Wh/kg)	Discharge Time (hr)	Range (km)
S.E.A.	64	6.4	352
Panasonic	50	5.0	275
Sears	41	4.1	225
Marathon	35	3.5	192



Pb-Acid Ni-Cd Ni-MH $Zn-Br_2$

Estimated Range of IDSEP van on the SFUDS

EV Battery	Specific Energy (Wh/kg)	Usable DOD (%)	Discharge Time (hr)	Range (km)
Panasonic	50	98	4.90	150
S.E.A.	64	60	3.84	117
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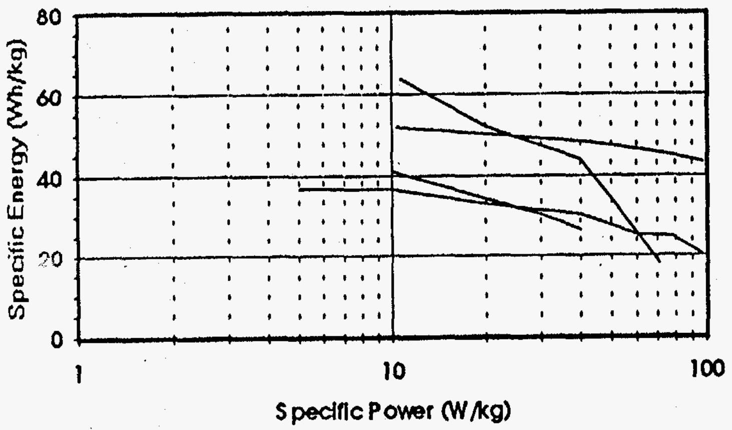
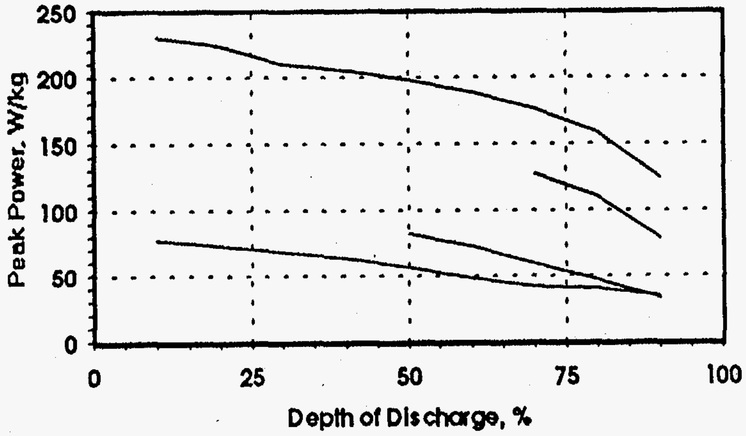




Pb-Acid Ni-Cd Ni-MH Zn-Br$_2$

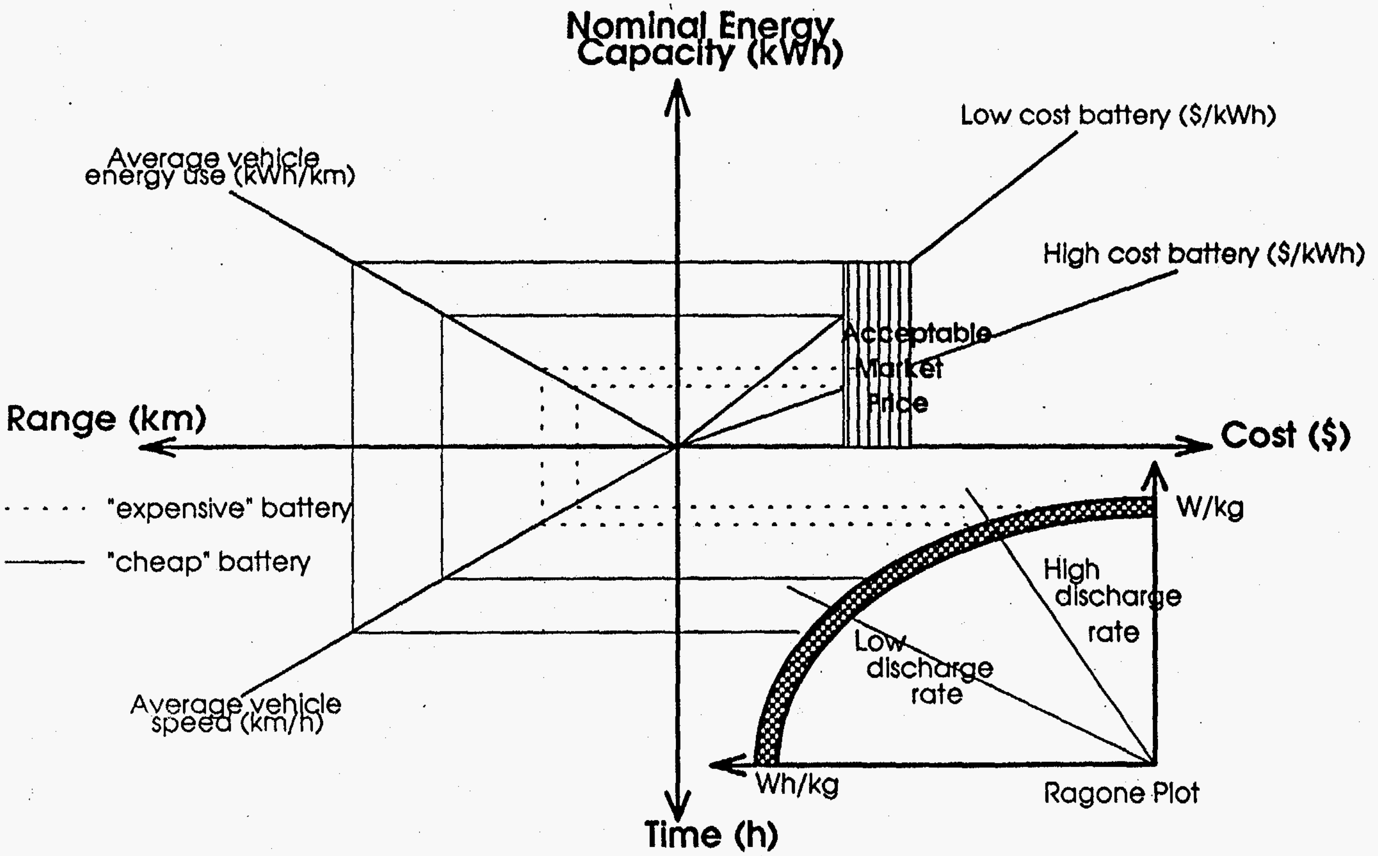
Comparison of Estimated and Simulated SFUDS Ranges

Battery Type	Simulated Range (km)	Estimated Range (km)	Error (%)
Panasonic	138	150	+ 8.5
Marathon	90	101	+ 12

Estimated Range of IDSEP Van with Cost ($5000) and Weight (695 kg) Limitations at a Constant 55 kph

EV Battery	Estimated Cost ($/kWh)	Energy (Cost) (kWh)	Energy (Weight) (kWh)	Range (km)
Sears	200	25.0	21.0	165
S.E.A.	250	20.0	20.0	157
Panasonic	600	8.33	8.33	66
Marathon	750	6.67	6.67	52

Relationship between Cost and Range



Summary

- The lead acid batteries have a low specific energy and moderate power density, but they are cheap and can be easily recycled.

- The nickel cadmium battery had a specific energy density slightly greater than lead acid, good power density and an anticipated long cycle life.

- The nickel metal hydride batteries have even better performance characteristics. A single Panasonic cell was cycled over 1000 times with less than 5% capacity loss.

- The zinc bromide battery has high specific energy, low power density and an anticipated long cycle life. The battery requires a control system for operation. The battery uses inexpensive raw materials and is flexible in design.

Conclusions

- The four battery technologies have individual strengths and weaknesses and each may be suited to fill a particular application.
- Regeneration will result in energy recovery levels that will be significant to vehicle range and thus worthwhile to implement.
- The lead acid battery is applicable to inexpensive, short range cars (NEV) and perhaps to larger package vans that can accept a heavy battery pack.
- Nickel based batteries may best fill the needs of high power, long range EV applications and perhaps a peaking battery.
- The zinc-bromide battery is probably best suited for long range, moderate performance EVs, e.g. commuter cars. This battery would benefit from power peaking hybridization.