STATISTICAL ANALYSIS OF PERFORMANCE DEGRADATION OF LEAD–ACID BATTERY UNDER SIMULATED ELECTRIC VEHICLE OPERATIONS*

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Summary

Controlled laboratory tests were conducted to evaluate the effects of selected electric-vehicle application factors on the performance and life of lead–acid batteries These factors included simulated driving profiles with different levels of peak power demands for vehicle acceleration, long rest times after charge or discharge, and different methods of recharging. The performance and life variations among cells and modules in a full-scale battery pack were also examined. The key factors affecting the performance and life of the battery were identified, and the rates of capacity and power degradation were quantified using multiple regression techniques. The analyses show that the most significant factors causing the performance variations and degradation were the levels of peak power demand by driving profile and the cell location within each six-cell module. The effects of charge methods and rest times were found to be small.

Introduction

The battery is a key element in the acceptance of electric vehicles (EVs), and R&D efforts are being undertaken to improve battery performance and lifetime. In a program sponsored by the Department of Energy through Argonne National Laboratory, the EV-2300 improved state-of-the-art lead–acid battery was developed by Johnson Controls, Inc. specifically for EV applications [1] In a program supported by the Electric Power Institute (EPRI), controlled laboratory tests were conducted at Argonne to evaluate the effects of selected application factors on the performance

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and life of the EV-2300 lead–acid battery These factors included simulated driving profiles with different levels of peak power demands for vehicle acceleration, long rest times after charge or discharge, and different methods of recharging The performance and life variations among cells and modules in a full-scale battery pack were also examined Some details of the tests have been reported previously [2, 3]

In this paper, the capacity and peak power data obtained from laboratory tests were analyzed to verify the statistical significance of test results, and to separate and quantify the effects of individual factors on the performance degradation of the EV-2300 lead–acid battery The observed laboratory test results might be deceptive because of (i) the inherent variability among cells and modules, (ii) the joint influence of several controlled variables such as peak power level, rest period, and charge method, and (iii) the inevitable variations of capacity and peak power capabilities resulting from changes in the uncontrolled variables such as cycle number, depth of discharge, etc The statistical analysis allows one to identify and quantify the key factors affecting the performance and life of the battery under EV operating conditions [4]

Laboratory tests and data

Two separate tests of the EV-2300 lead–acid battery were performed at Argonne The first one, as described in ref 2, used six individual modules to test the effects of three different operating variables driving profile peak power levels, location of open-circuit periods, and charging methods The constant-current discharge tests also provided a basis for comparison The test matrix is summarized in Table 1

TABLE 1

Test matrix summary of the six-module tests

Discharge	Power (W kg^{-1})		Charge method	OCAC (h)	OCAD (h)	End-of-life (cycles)	End-of-test (cycles)
	Peak	Avg.					
DP	57	15	CI/CV	8	0	178	272
DP	57	15	CI/CV	0	8	179	286
DP	35	15	CI/CV	8	0	257	319
DP	35	15	CI/CV	0	8	378	454
CI at $C/3$	12	12	CI/CV	*	*	538	605
CI at $C/3$	12	12	CI/CI/CI	*	*	425	487

Abbreviations
OCAC = Open-circuit after charge
OCAD = Open-circuit after discharge
DP = Driving profile (SAE J227aC/VW van)
CI = Constant current
CV = Constant voltage
* = Open-circuit time as required to reach 28 °C

The $C/3$ ampere-hour capacities of each of 36 individual cells from all six modules were measured near the end of the tests. The accumulated charge/discharge cycles when cell capacity data were taken ranged from 272 to 605. To provide more complete representation of capacity variation over entire battery life, additional module capacity data from earlier stages of life (from cycle 4 to 12) were added to the data set.

The second test used a full-scale 12-module battery pack for life-cycling and system evaluation. The cell ampere-hour capacity and peak power data were sampled from three modules (18 cells) selected from the battery pack. The three selected modules — modules #9, #3, and #6, failed to meet peak power requirements of the driving profile at 275, 310, and 341 cycles, respectively, during the battery-pack cycle life test More details on the conditions and results of the battery-pack test were described in ref. 5. These data were analyzed for performance degradation as well as for the variations among cells and modules within the battery pack. The results were also compared with that obtained from the six-module tests.

Method of analysis

The statistical method used to establish the relationship between the battery performance and the factors affecting it was the multiple regression analysis Two dependent variables (the variables whose variations are to be explained) were considered in the analysis (i) the measured ampere-hour capacities of individual cells at $C/3$ constant-current discharge, (ii) the module peak power capability calculated from the current–voltage responses under driving profile tests.

Through the regression analysis, each of the two dependent variables was quantitatively related to several independent (or "explanatory") variables, some of them were experimentally controlled, some were not. The controlled variables considered were the level of peak power demand, the resting period, and the charge methods, etc The uncontrolled variables, such as cycle number, depth-of-discharge (number of driving profile stop/starts completed), and cell location, were also included in the independent-variable list to explain, together with the controlled variables, the variation of the dependent variable.

The statistical significance of the relationship between the dependent variable and each of the independent variables was tested based on the t-ratio of the regression coefficient of each variable. If the coefficient was statistically insignificant, *i e*, the independent variable had caused no significant variation of the dependent variable, the variable would be dropped from the regression equation The effects of the key factors on the dependent variable were thus separated and quantified by the final regression equation and its coefficients. The results of the capacity and peak power analyses are reported separately in the following sections

Cell capacity variation and degradation

Because of the different natures of the six-module test and the battery-pack test, the data from these two tests were analyzed separately The results of the analysis of these two data-sets were then compared to check the consistency

(i) Analysis of six-module test data

The $C/3$ ampere-hour capacities of 36 individual cells from the six-module test were analyzed by multiple regression technique Figure 1 is a plot of the raw capacity data *versus* their corresponding cycle numbers

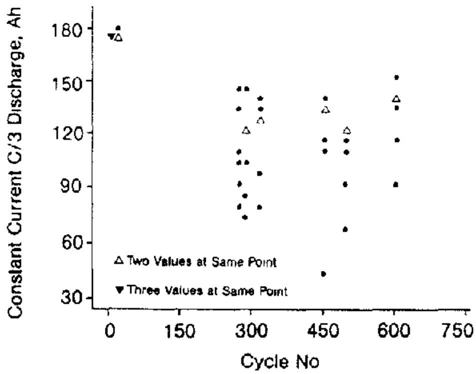

Fig. 1 Capacity data from the six-module tests Module capacities at the beginning-of-testing are shown and the capacities of individual cells within each module at the end-of-testing for that module are also shown

The capacity data were regressed against several independent variables such as peak power level, resting times, charge method, cell location, cycle number, module number, etc , to test if any relationship exists between these variables and cell capacity. For this purpose, variables other than capacity and cycle number were treated as categorical variables, *i e* , having values either 0 or 1 for each of the designated conditions The cell numbers were used to identify cell locations, for example, cell 1 referred to the cell located at the negative terminal, and cell 6 at the positive terminal, etc

During the regression, a variable would be eliminated from the regression equation if the t-statistics of its coefficient were less than 2, *i e* , the relationship between cell capacity and the variable was statistically insignificant at the 95% confidence level After eliminating insignificant variables, the remaining variables for explaining the capacity variations were cycle number, peak power levels, charge methods, and cell locations The numerical results of the regression are shown in Table 2

The final regression equation for capacity data consisted of a constant plus several explanatory terms cycle number (CYL), plus the product of cycle number (CYL) with peak power level (PPL), charge method (CM),

TABLE 2

Regression analysis of cell capacity variation from six-module test data

Variable	Coeff.	St Dev	t-Stat	% Expld
Constant	173 23	7 52	23 0	
CYL	−0 156	0 024	−6 5	21 3
PPL57*CYL	−0.161	0 027	−5 9	15 4
PPL35*CYL	−0 074	0 019	−3 3	9 1
CMCI*CYL	−0 027	0 020	−3 3	5 0
C1*CYL	0.068	0 025	2 7	
C2*CYL	0 098	0.025	3 9	
C3*CYL	0 116	0 025	4 6	23 4
C4*CYL	0 072	0 025	2 8	
C5*CYL	0 114	0 025	4 5	
	F-Stat = 10 3		R-Square = 74 2%	

Abbreviations
CYL = Cycle number
PPL57 = Level of peak power demand at 57 W kg^{-1}
PPL35 = Level of peak power demand at 35 W kg^{-1}
CMCI = Charge method by CI/CI/CI
C1 - C5 = Cell locations 1 - 5, cell no 1 located nearest to negative terminal
Note The capacity data were measured under constant-current discharges at $C/3$ rate

and cell location (C1 - C5). Note that in this analysis, cell 6 was chosen as a reference. The need to multiply each independent variable by cycle numbers shows that the effects of these variables change as cycle number increases. A high degree of correlation between the cell capacity and these independent variables is shown by the t-ratios of greater-than-two for the regression coefficients of each variable. The effect of rest times on cell capacity was found to be insignificant. The results show that cells in locations 1 - 5 behave similarly but significantly differently from cell 6

The goodness of overall fitting between the data and regression equation is shown by the R-Square value of 74.2%. In other words, 74 2% of the total variations in cell capacity data could be explained jointly by these independent variables. Of this 74.2%, 21.3% of capacity variations were explained by cycle number, 24.5% by peak power levels, and 5 0% by charge methods. An additional 23.4% of capacity variations could be explained by the cell locations.

The magnitude of the effect of each independent variable on cell capacity was indicated by the regression coefficient for each variable. The constant term of the regression equation showed that statistically the nominal cell capacity for all cells at cycle 0 is 173.2 A h. The coefficient for cycle number (CYL), −0.156, indicated that, for cell no 6 cycled at $C/3$ discharge, the capacity decreased by 0.156 A h/cycle as the number of cycles increased. The coefficients of C1 - C5 terms measured the differences in capacity degradation rates between cells 1 - 5 and cell 6 The positive values of all five coefficients indicated that cells 1 - 5 performed better, *i.e.*, had slower rates of capacity degradation, than cell 6. For example, the rate of degradation for cell 1 was 0.068 A h/cycle slower than cell 6, or at the rate of 0.088 A h/cycle The consistency of the result was also illustrated by the fact that each cell location shows the same standard deviation.

The effect of the level of peak power demand (PPL) on cell capacity was also quantified by the coefficients of the PPL terms in Table 2. The rate of capacity degradation increased by 0.161, from 0 156 to 0.317 A h/cycle, if the battery were cycled under driving profiles of 57 W kg^{-1} peak power level instead of under *C*/3 constant-current discharges The rate of degradation would increase by 0 074, from 0 156 to 0 230 A h/cycle, if cycled under a driving profile of 35 W kg^{-1} peak power level The results showed that the higher the peak power level of discharge, the faster the cell capacity degraded at *C*/3

Similarly, the effect of charge method on cell capacity could be determined from the regression coefficient in Table 2 Cells charged by CI/CI/CI showed a negative effect of −0 027 A h/cycle when compared with cells charged by CI/CV. In other words, charging at CI/CV was preferred to the three-level constant-current charging. However, because of the small coefficient, the effect of charge method was minor compared with the effects of peak power levels and cell locations

(ii) Comparison with battery-pack test results

The same analysis was also performed on the cell capacity data from the twelve-module battery pack test A total of 45 cell capacity data were regressed against variables such as cell locations, cycle number, module number, etc Other variables, such as peak-power level, charge method, and rest times, were not included in the analysis because they were not part of the test conditions in the battery-pack test Nevertheless, the capacity variation and degradation upon cycling were still observable from the data

After insignificant variables had been dropped, the remaining independent variables were cycle number and the products of cell locations and cycle number The results of the regression are shown in Table 3 The final regression equation consists of a constant term and five independent variables cycle number and cell locations 2 - 5 multiplied by cycle number The results showed that the four inner cells, 2, 3, 4, 5, in these six-cell modules, are significantly different from cells 1 and 6, the two end-cells

The R-Square value of the regression was 79 7% Of this 79.7%, 62.2% of capacity variations were explained by cycle number alone An additional 17 5% of capacity variations were explained by the products of cycle number and cell locations.

The constant term of the regression equation indicates that the nominal cell capacity for all cells at cycle 0 is 177.8 A h. The coefficient for the cycle number, −0 288, indicates that, for cells 1 and 6, the capacity decreases by 0 288 A h/cycle as the cycle number increases The coefficients of the

TABLE 3

Regression analysis of cell capacity variation from battery-pack test data

Variable	Coeff	St Dev	t-Stat	% Expld
Constant	177 85	5 64	31 5	
CYL	−0 288	0 078	−12 2	62 2
C2*CYL	0 078	0.027	2 9	
C3*CYL	0 134	0 027	5 0	17 5
C4*CYL	0 107	0.027	4 0	
C5*CYL	0 098	0.027	3.6	
	F-Stat = 30 6		R-Square = 79 7%	

Abbreviations
CYL = Cycle number
C2 - 5 = Cells 2 - 5

TABLE 4

Comparison of capacity degradation analyses of the six-module data and the battery pack data

	R2	Nominal capacity (A h)	Dchg profile	Degradation rate	
				Cell 6 (A h/cycle)	Cell 3
Pack data	0.797	177 8	Mixed	−0 288	−0 154
Module data	0 742	173.2	pp = 57 W kg^{-1}	−0 317	−0 201
			pp = 35 W kg^{-1}	−0 230	−0 114
			C/3	−0 156	−0 040

Abbreviations
R2 = R-square of regression analysis
pp = Peak power level of driving profile

terms for cells in locations 2 - 5 showed how their capacity degradation rates differed from the two end-cells. The positive values of all four coefficients indicate that cells 2 - 5 perform better, *i e*, have slower rates of capacity degradation, than cells 1 and 6 For example, the rate of degradation for cell 2 is 0.078 A h/cycle less than that of the end-cells (−0 288), or at a rate of −0.210 A h/cycle.

The results of the six-module tests were compared with the battery-pack test in Table 4. The two sets of results were consistent. Both data showed the negative effect of cycle number and the poorer performance of the end-cells. The capacity degradation rates of battery-pack data fell in between the rates for the modules tested with PP = 57 W kg^{-1} and 35 W kg^{-1}, reflecting the fact that the 12-module battery pack was cycled under a combination of both driving profiles. This also reconfirmed the negative effect of the higher peak power level of the driving profile on the capacity degradation of the EV-2300 battery. Based on the results of the six-module

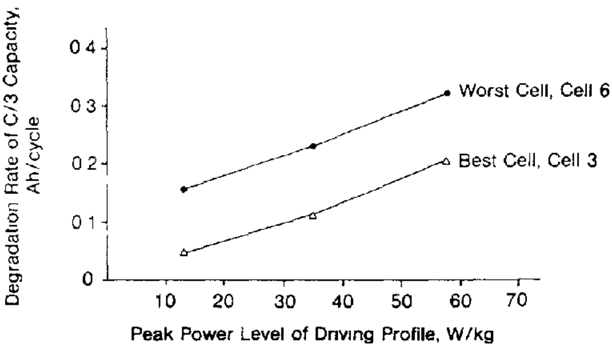

Fig 2 Effect of peak power level on degradation rate of $C/3$ capacities

tests, the effect of the peak power demand on the degradation rates of the $C/3$ capacities is shown in Fig 2 The results for the best cell, represented by cell 3, and the worst cell, represented by cell 6, are compared. The Figure shows that the capacity degradation rates increase as the power levels of the driving profiles increase. It also shows the difference in degradation rates between good and bad cells

Peak power degradation

In a similar manner to that of the above analysis of capacity data, the peak power data from the six-module tests were separated from the battery-pack data. A comparison was made after each set of data was analyzed.

(i) Analysis of six-module test data

The specific peak power (W kg^{-1}) of four EV-2300 modules at various cycle numbers and depths-of-discharge was calculated from the voltage–current data obtained during the six-module driving profile tests A total of 193 peak power data covering two different driving profiles, 12 selected cycles, and 7 different depths of discharge, were used in the analysis

To explain the observed variations in peak power data, several independent variables such as cycle number, levels of peak power demand, rest times, module number, and depth-of-discharge, etc , were used to regress against the peak power data Since the energy delivered per profile was maintained constant at about 0 37 W h kg^{-1}, the number of driving profiles discharged in each cycle was used as a proxy for depth-of-discharge (on a watt hour basis) Following the same procedure in the capacity analysis, the independent variables were eliminated from the regression equation if the t-statistics for the coefficients were statistically insignificant

The results of the regression analysis are shown in Table 5 The final regression equation consisted of a constant term and four independent variables cycle number (CYL), number of driving profile stop-starts (DP)

TABLE 5

Regression analysis of peak power variation from six-module data

Variable	Coeff	St Dev	t-Stat	% Expld
Constant	127 27	0 762	166 9	
DP*DP	−0.0059	0.0004	−16 0	54 4
CYL	−0 0690	0 0051	−13 6	32 2
DP*CYL	−0 0008	0 0001	−6 7	1 2
PPL57*DP*CYL	−0 0016	0 0001	−13 4	5 3
RTAC*DP*CYL	−0 0007	0.0001	−8 4	2 0
	F-Stat = 712 5		R-Square = 95 1%	

Abbreviations
DP = No of driving profiles within each cycle
CYL = Cycle number
PPL57 = Level of peak power demand at 57 W kg^{-1}
RTAC = Resting time (open-circuit) after charge

representing the depth-of-discharge, levels of peak power demand (PPL), and rest times (RT). The effect of depth-of-discharge on peak power was found to be nonlinear, thus the second order term was used for the variable DP. The interactions among independent variables also needed to be considered to provide a better accountability for the variation of peak power data, for example, the product of cycle number and driving profile number was used to represent the changing effect of depth-of-discharge as cycle number increased. Similarly, the effects of peak power level and rest times changed with cycle number.

The R-Square value of the regression is 95 1% In other words, 95.1% of the total variations in peak power can be explained jointly by the independent variables used. Of this 95.7%, 54.4% of the peak power variations were explained by the number of driving profiles discharged (*i e* , depth-of-discharge), 32 2% by the cycle number, and 1 2% by the product of driving profile and cycle number. An additional 5.3% and 2.0% of peak power variations were explained by the different levels of peak power demand in the profile and by the different rest times

The constant term of the regression equation, 127.3 W kg^{-1}, represented the nominal specific peak power of the modules at the first cycle and 0% depth-of-discharge. The coefficient for cycle number, −0.069, indicated that it alone accounted for 0.069 W kg^{-1} per cycle decrease in peak power The negative coefficient for DP*DP, −0.0059, also indicated that specific peak power decreased nonlinearly as the number of driving profile start/stops (or the depth-of-discharge) increased, as shown in Fig. 3. For example, at the end of the 50th driving profile in a discharge cycle (*i e* , about 65% depth-of-energy capacity), the specific peak power of the battery would be 14.8 W kg^{-1} less than that at the beginning of the discharge The coefficient for CYL*DP, −0.0008, indicated additional degradation due to the interaction of cycle number and depth-of-discharge

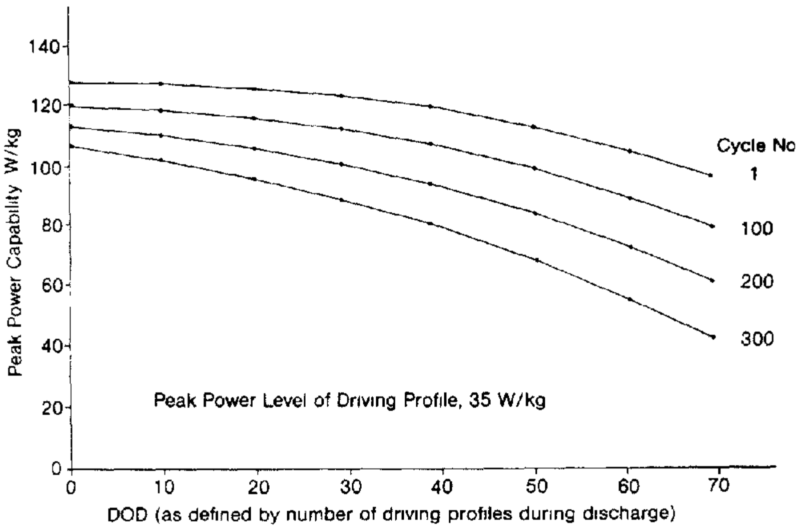

Fig 3 Effect of depth-of-discharge (DOD) on peak power capability of EV-2300 battery at different stages of cycle life

The effect of discharging the battery at higher power levels of driving profiles can also be determined from the coefficients in Table 5 The coefficient, −0.0016, showed that if the module was cycled under the 57 W kg^{-1} driving profile instead of the 35 W kg^{-1} profile, the peak power capability of the battery would degrade faster by 0 0016 W kg^{-1} per profile per cycle. The results also indicated a small negative effect of open-circuit after charge, rather than after discharge, on the peak power of the battery.

To see how well the regression analysis explained the peak power variations, the peak power calculated from the regression equation is plotted against the observed data in Fig 4. The calculated peak power data were in good agreement with the observed data over the entire range of the cycle life of the battery.

(ii) Comparison with battery-pack results

The specific peak power data were obtained from three EV-2300 modules selected from the twelve-module battery pack. A total of 165 peak power data covering two different profiles, 7 selected cycles, and 15 different depths of discharge were used in the analysis The peak power data were regressed against cycle number, module number, and depth-of-discharge, etc. The number of driving profiles discharged in each cycle was again used as a proxy for the depth-of-discharge. The module number, treated as a dummy variable, was used in regression to see if the peak power behavior of the three modules belonged to the same sample population.

The results of the regression analysis are shown in Table 6. The final regression equation consisted of a constant term and two independent variables cycle number (CYL) and the number of driving profile stop-

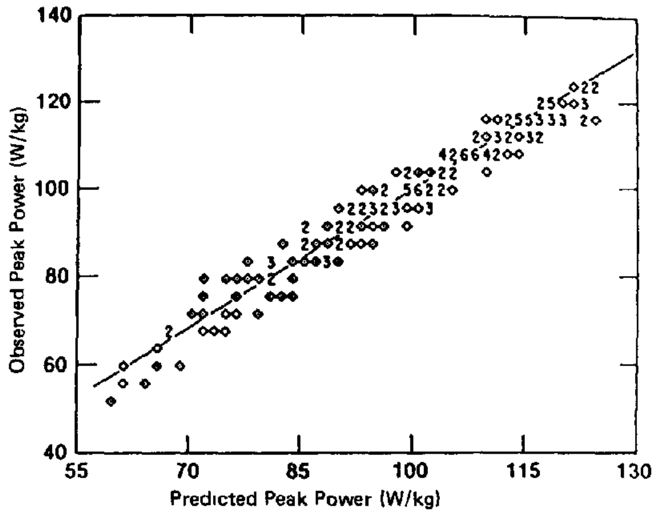

Fig 4 Calculated *vs* observed power for EV-2300 cells (The numbers indicate the number of overlapping points, the diamonds indicate a single point)

TABLE 6

Regression analysis of peak power variation from battery-pack test data

Variable	Coeff	St Dev	t-Stat.	% Expld.
Constant	122 54	1 133	108 2	
DP*DP	−0 007	0 0003	−20 5	43 7
CYL	−0.147	0 0074	−19 8	51.2
DP*CYL	−0 0008	0 0001	−5 5	0 8
	F-Stat = 1193 8		R-Square = 95 7%	

Abbreviations
DP = No of driving profiles within each cycle
CYL = Cycle number

starts (DP) representing the depth-of-discharge After the effects of cycle number and depth-of-discharge were accounted for, the differences among three modules were found to be insignificant, *i e* , the three belonged to the same sample population.

The R-Square value for the regression is 95.7%. Of this 95.7%, 43.7% of the peak power variations were explained by the square of the number of driving profile stop-starts completed (*i e.*, depth-of-discharge), 51.2% by the cycle number, and an additional 0.8% by the product of driving profile and cycle number.

The constant term of the regression equation, 122.5 W kg^{-1}, represents the nominal specific peak power of the modules at cycle 0 and 0% depth-of-discharge. The coefficient for cycle number, −0.147, indicates that considering the effect of cycle number alone, the peak power would decrease by 0 147 W kg^{-1}/cycle as the cycle number increases The negative coefficient for DP*DP, −0 007, also indicates that specific peak power decreases non-linearly as the number of driving profile start/stops (or the depth-of-discharge) increases The coefficient for CYL*DP, −0 0008, indicates additional degradation due to the interaction of cycle number and depth-of-discharge The t-statistics for all three coefficients are much greater than 2 0

The comparison of the results from the battery-pack test with the six-modules test is shown in Table 7 The comparison showed that the peak power analyses for the two data sets are consistent The rates of peak power degradation of EV-2300 batteries during driving profile discharges are reconfirmed by the battery pack data

TABLE 7

Comparison of peak power analyses of the six-module data and battery data

	No data	R2	Norm SPP	Driv profile	Power degrad	
					DOD–5DP	60DP
Pack data	165	0 957	122 5	Mixed	−0 187	−0 195
Modules	193	0 951	127 3	PP = 57	−0 191	−0 215
				PP = 35	−0 112	−0 120

Note
R2 = R-square of the regression analysis
SPP = Specific peak power in W kg^{-1}
DOD = Depth of discharge defined on W h kg^{-1} basis
DP = No of J227aC/VW-Van driving profiles delivered during discharge, a proxy for DOD, the energy delivered per profile is maintained constant at about 0 37 W h kg^{-1}, the no of DP completed by an EV-2300 module (for PP = 57) at the beginning of the test was 78

Conclusions

Statistical methods were used to analyze the laboratory data of EV-2300 lead–acid batteries tested under simulated electric vehicle operations. The effects of EV operating factors, such as the levels of peak power demand, rest times, and charge methods, etc., on the degradation of battery capacity and peak power, were clarified and quantified using multiple regression techniques. The capacity variations among cells within each module were also examined

The analyses show that the most important factors causing the performance variation and degradation were the levels of peak power demand by the driving profile and the cell location within each six-cell module The effects of charge methods and rest times were found to be small

As the level of peak power demand increased, the degradation of battery capacity and peak power capability was accelerated The rate of capacity degradation increased from 0.230 to 0.317 A h/cycle as the peak power level of the driving profile (SAE J227aC for a Volkswagen van) was increased from 35 to 57 W kg^{-1} For the same change in the level of peak power demand, the degradation rate in peak power capability of the battery increased from 0.112 to 0.191 W kg^{-1}/cycle. In other words, the rate of degradation of peak power capability and capacity with cycle number is approximately proportional to the peak power demand of the load. For example, increasing the peak power demand from 35 to 57 W kg^{-1} caused about a 75% increase in the degradation rates of both capacity and peak power capability. The effects of peak power demand on the degradation rates of battery peak power capability at different depths-of-discharge are shown in Fig 5. The results indicate that

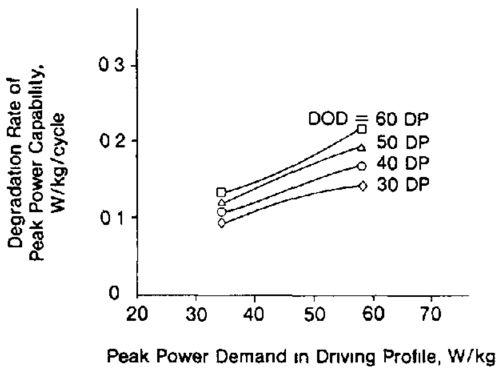

Fig 5 Effect of peak power demand in driving profiles on the degradation rates of EV-2300 peak power capability at different depths-of-discharge (The DOD is determined from number of driving profiles completed)

(i) to obtain realistic data on battery life under EV operation, it is important to conduct cycle-life tests using a load profile representative of the application;

(ii) the load profile for the intended application should be an important consideration in battery design and development;

(iii) research is needed to understand the underlying reasons for increased degradation rates under load profile conditions.

The test data from 54 cells (out of 9 modules) also indicated that the two end cells in each six-cell module had consistently higher rates of capacity degradation than the middle cells. On average, the difference in capacity degradation rates between middle cells and end cells was about 0.11 A h/cycle In most cases, the module capacities were eventually limited by these end cells In terms of module cycle life, the cell location can affect cell life by as much as a factor of two. This indicates that improved design offers the possibility of achieving considerably improved battery life. The degradation analysis of test data of the full battery pack agrees with that of the individual modules for similar test conditions, this indicates that no significant additional scale-up factor affects the cycle life of the battery pack

The results of the statistical analysis also indicated the degree of manufacturing variation in the EV-2300 battery. Based on the analysis results, 50.8% of the total variations in $C/3$ capacities among *all* cells were attributed to the differences in cycle number and charge/discharge conditions, another 23.4% of the variations were correlated with cell locations, the remaining 25 8% were unexplained The 50 8% variations are simply due to the different conditions imposed during the tests, they are not related to the manufacturing variations.

On the other hand, the 23 4% representing the variations of cells within the module, and the 25 8% representing the inherent variability within or among the modules, are likely to be related to the cell manufacturing variations and the module design factors, such as uneven compression, improper watering, and poor temperature distribution Furthermore, since manufacturing variations are unlikely to correlate with cell locations, the 23 4% variations are probably due to module design factors, and not to the manufacturing processes. The effect of manufacturing processes is most likely to show up in the unexplained 25 8%.

In summary, although the total variation of cell capacities within each module is large, only part of the variation (about 25%) is attributable to the cell manufacturing processes. A significant portion of the cell capacity variations within the module is related to the module design factors such as uneven compression among cells at different locations. The effects of these design factors become more apparent as the number of cycles increases

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