RATIONALE AND METHODOLOGY FOR GROUP TESTING OF ELECTRIC VEHICLE BATTERIES

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1. Introduction

Testing batteries in both the laboratory and in vehicles is an important part of evaluating new batteries and electric drivelines for electric vehicles. In the development of a new battery design, tests are made of cells, modules, and packs. The initial tests are made using cells and later, modules consisting of a number of cells are tested. Finally, a number of modules in a pack are tested in a vehicle. In all cases the tests should be made in such a way that the results are meaningful for realistically assessing the use of the new battery in an electric vehicle application (*i.e.*, particular vehicle design and use-pattern).

An electric vehicle owner is primarily interested in four factors concerning the battery:

(i) performance (vehicle range (mi) and acceleration),

(ii) charging energy efficiency and maintenance (how difficult is it to charge and care for the battery),

(iii) lifetime (how long (yrs) will the battery last before it must be replaced),

(iv) the cost ($) of a new battery.

Most battery tests are performed to gain information pertinent to factors (i) - (iii). The fourth factor (cost) impacts the other three factors in that it is often possible to improve factors (i) - (iii) if increasing cost is permissible. The performance, maintenance, and lifetime of a battery is strongly dependent on the discharge and charge profiles (*i.e.*, use-pattern) which the battery experiences. Hence, battery test data that encompass the use-pattern of potential interest in electric vehicle usage are needed to evaluate a battery for particular applications. It should also be recognized that batteries used in an electric vehicle experience transient discharge conditions in actual service and thus steady current (or power) discharges are of limited value in assessing battery performance and life in that application.

Another aspect of the electric vehicle application of batteries is that the cells are not used individually, but rather in packs consisting of 30 - 150 cells or 10 - 50 modules in series. The response of the battery pack to a given power demand is then the sum of the individual responses of the 10 - 50 modules. Unfortunately each of the modules is not identical and the variability between modules becomes more significant at large battery currents. Hence it is not adequate to assess the response of a battery pack based on the mean characteristics of a few modules, especially when the battery pack experiences high transient battery currents. The variability of battery modules is due to the variability between cells resulting from small variations in the manufacturing processes. Cell and module variability can presently only be determined by testing groups of cells and modules over a range of discharge conditions. The change in cell/module variability with repeated high-rate discharges is undoubtedly an important factor in understanding the aging of modules and packs. Cell/module variability and its effect on battery pack performance and life has received relatively little study and is the prime concern of this paper.

2. Test procedures for battery group testing

The rationale behind battery group testing is simply that battery cells and modules manufactured using present fabrication processes and quality control are not sufficiently identical that their variability can be ignored or even averaged to determine the high current discharge characteristics of a battery pack consisting of 30 - 150 cells or 10 - 50 modules. This almost unavoidable variability in cells/modules becomes more important as the battery pack experiences higher current pulses and is subject to irregular daily use-patterns. The trend in electric vehicle design is toward higher acceleration performance and thus greater peak power demands on the battery. Hence it is likely that module variability will become even more important in the future than in the past. In this section of the paper, test procedures which permit a quantitative determination of cell/module variability, and its effect on battery performance and life, are discussed.

Group testing involves testing a number of cells or modules in series and taking data on the behavior of each cell or module individually. It is important that the cells/modules selected for test be typical, and not hand-picked or pre-tested to be above-average in uniformity. The group test data can then be analyzed to determine the cell or module variability and its change with discharge and charging profiles. The data would also be used to relate the group characteristics to the mean behavior of the individual cells or modules and their variability. Determining the effects of transient pulsed discharge and irregular depths-of-discharge before recharging would be of particular importance. A major difference between testing a group rather than single cells or modules is that many more data would be acquired in a short period of time with the voltage (and temperature) of each cell or module being taken in a time small compared with that in which it changes significantly. This would require the use of a high-speed data acquisition system. Such systems are readily available now even utilizing personal computers (*e.g.*, IBM PCXT).

2.1. *Test instrumentation*

The test instrumentation which would be used in group testing is essentially the same as that utilized in the present testing of the transient response (to pulsed discharge or charging) of battery cells, modules, or packs. Of special interest in this regard is the sensor instrumentation described in ref. 2 for use in the microprocessor-controlled electric and hybrid vehicles built for DOE. A schematic of a group test facility showing six test cells or modules is given in Fig. 1. The voltage of each individual unit would be read during each sampling sweep and stored in the data acquisition computer. The sampling sweeps could be taken each second or at any interval appropriate for the test being performed. The voltage and current of the total group would also be taken before and after the sampling sweep and those data would also be stored in the computer. Temperature would also be measured, but it could be sensed at less frequent intervals.

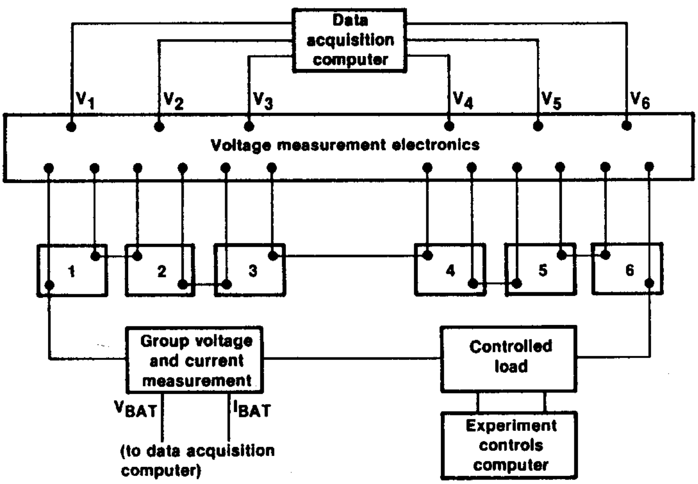

Fig. 1. Schematic of a battery group test facility.

2.2. *Test control*

As shown in Fig. 1, the group test facility would be controlled by a computer. By control is meant regulation of the discharge and charge profiles and termination of either the discharge or charge events. The control computer would be programmed to obtain sets of discharge profiles corresponding to representative electric vehicle use-patterns in terms of both the driving cycle and daily range. The control during discharge would be based on power–time histories, $P(t)$, which would include periods of rest as well as peak power accelerations and regenerative braking. The battery units could be tested using regular discharge/charge profiles, as is usually done at present, or irregular profiles, as is more realistic of actual electric vehicle use. It is also possible to develop software which would permit input of the vehicle design parameters (vehicle weight, battery weight, peak electric drive-line power, and customer use-pattern) so that the computer would calculate appropriate sets of power–time histories for cycling the battery.

2.3. Data correlation and interpretation

A group test would produce large volumes of data in that the terminal voltage and temperature for each module would be stored (recorded) for each sampling sweep. This is in addition to the pack data. Reduction, analysis, and graphical presentation of the data can best be done utilizing the data acquisition computer. This would require development of special software. In this way, data could be analyzed during an on-going experiment when that is deemed to be advantageous.

There are many ways in which a group test can be performed and the data correlated and analyzed. The following discussion is given for purposes of illustration and is not meant to be all-inclusive or complete. Since very little data on module variability are available, the group tests would start with constant current discharges of N modules connected in series. For each sampling time, the average module terminal voltage is equal to the pack voltage V_{pk} divided by N. Hence, for each discharge rate (I), the standard deviation $\sigma_{V,I}$, of the module terminal voltage distribution can be calculated as a function of pack depth-of-discharge (DOD = $AH/(AH)_{cap,pk}$). In other words,

$$\sigma_{V,I} = \sigma_{V,I}(\text{DOD}, I)$$

would be determined. σ_V could be used as a simple measure of module variability. Its variation with discharge rate would be of particular interest. The next step in the analysis of the constant-current group test data could be to determine the Puekert curve for each module for comparison with the corresponding curve for the pack. This would involve a regression analysis (least squares best fit) of the discharge time, t_D (to a specified cut-off voltage), of each module as a function of discharge current I. Statistical methods can be used to determine the correlation coefficient, β, for the curve fit for each module and, further, the confidence level that the module correlations are from data sets that are distinct from the pack and their differences related to $\sigma_{V,P}$.

Constant-current and constant power discharges of the group could be done periodically during charge/discharge cycling of the group to determine the effect of battery aging on $\sigma_{V,I}$, $\sigma_{V,P}$, and the Puekert curve. In other words, it is possible to show that the differences between the module and pack results are statistically significant and due to module variability and not due to voltage measurement error. The relationships between the differences in the module and pack Puekert curves and the module variability, as given by σ_V would be studied.

The group experiments could be repeated utilizing constant power rather than constant current. In this case the power contribution of each module would vary, with the total power delivered being

$$P = \sum_{j=1}^{N} P_j$$

with the average power being P/N. The average voltage would be $V_{AV} = V_{PK}/N$ as in the constant current discharge case. The standard deviation, $\sigma_{V,P}$ could be calculated and correlated as

$$\sigma_{V,P} = \sigma_{V,P}(P, \text{DOD}).$$

This is another measure of module variability. In a manner similar to that used for the Puekert curve, the constant-power data for various power levels could be used to determine the Ragone curves for the modules and pack and their differences related to $\sigma_{V,P}$.

Constant-current and constant power discharges of the group could be done periodically during charge/discharge cycling of the group to determine the effect of battery aging on $\sigma_{V,I}$, $\sigma_{V,P}$, and the Puekert and Ragone curves. Pulsed discharging of the group of modules could also be done and the variability of the V *versus* I, DOD correlations determined for the modules. The number of modules, N, required to attain a specified statistical significance (confidence level) in the results will depend on the variability of the modules and would have to be determined after the fact.

The relationship between module variability and variations in physical characteristics of the modules, such as weight, could also be determined. Variations in internal characteristics of the modules would require teardown of selected modules, but this is also possible.

The foregoing discussions indicate the type of group tests that could be performed and the ways in which the data could be correlated and analyzed. Many other possibilities certainly exist and could be pursued if initial results indicate that they would be profitable. The prime objectives of the initial tests would be to quantify the module variability and show its impact on pack performance and life and, in addition, investigate how this variability is related to variations in the physical characteristics of the modules and differences in manufacturing processes. The initial experiments would likely be performed using lead–acid modules, but the group testing of other battery types, such as NiFe, would also be of considerable interest.

2.4. *Time and cost*

Group testing of batteries will certainly be more expensive and time consuming than tests of single cells and modules where little attempt is made to evaluate variability and its effect on battery performance and life. A Group Test Facility requires a higher voltage and higher current controlled load than most battery test facilities presently have. The cost of cycling equipment increases with voltage and maximum current. In addition, the response time of the instrumentation and data acquisition equipment must be fast in order to sample the group at sweep intervals of one second or maybe less. The cost of developing the software for data reduction and correlation could also be relatively high. It is also clear that more cells or modules would have to be available for testing if the group testing method is used. This would also add to the time and cost of evaluating a battery design. This added cost and time in battery testing, however, would yield information that would permit the realistic evaluation of batteries for electric vehicles prior to dynamometer and field tests using vehicles and, in addition, would permit the collection of data which is more difficult to take in the vehicle tests.

The recent interest in Battery Management Systems (BMS) is an indication of a recognition of the unique behavior of battery packs as compared with individual modules. This important information can be obtained reasonably early in battery development programs using group testing techniques, and the results used to set variability specifications for battery manufacture. The total cost of battery development to achieve a battery which functions satisfactorily in electric vehicles on the field would thus be reduced, even though initial testing costs would likely be higher.

3. Application of battery group test results

3.1. Battery R&D and manufacture

Battery group test results are important to both battery developers and vehicle designers. In the case of the battery developer the group test results yield an indication of the adequacy of their quality control in terms of its effect (variability) on battery performance and lifetime for realistic use-patterns. The variability of the cells and modules can be related to physical characteristics of the batteries, such as module/cell weight, plate active-material weight, plate porosity, etc., which can be determined from cell/module teardown analyses. By closing the loop between battery manufacture and performance, battery manufacturing quality control specifications can be set in a rational manner.

3.2. Vehicle design and field evaluation

In designing an electric or hybrid (heat engine and electric drive) vehicle, sizing the battery pack to meet given range (mi) and peak power specifications is a very critical decision. If the designer is to use an existing battery (that is, one that can be purchased) he must have sufficient data available to assess the battery pack performance in the vehicle being designed. This is often done using a computer simulation in which the battery is modeled. The battery model is usually based on module data and no account is taken of the effect of module variability on pack performance, even though the application may require the battery to sustain high peak power (high W/kg) pulses and be used to high depths-of-discharge (DOD of

80% or higher). This is done because data to do otherwise are not available and there is no rational way to degrade pack performance to account for unknown module variability. The result can be an electric or hybrid vehicle that does not meet its design goals.

If the vehicle designer is to use a new battery that is to be developed especially for the vehicle he is designing, then it is necessary for him to set the battery specifications. Vehicle simulations are often used to set the specifications and a battery model is set-up which is thought to be consistent with those specifications. The battery developer then designs, fabricates, and tests cells which are intended to meet the vehicle designer's specifications. The cell tests are often constant current discharge tests at the $C/3$ - $C/1$ rate. In some cases, pulsed power tests are made to determine the power density and internal resistance of the cells if such specifications were given. Little or no attention is given to cell variability or its likely effect on module and pack performance. If most of the cells meet the specifications, then work is started on the fabrication of modules. Testing of the modules by the battery manufacturer is often less extensive than testing of the cells. A selected number of modules are tested by the battery developer; if these, on the average, meet the specifications, the modules are assembled into packs (usually three or less) of 10 - 20 modules. The packs are then shipped to the vehicle fabricator to be tested in the car. Several modules may be shipped to the NBTL for the normal characterization testing. It is always assumed that since the batteries (cells and modules), on average, meet the specifications, the pack will perform in the vehicle as planned. At each testing step along the way little attention is given to cell or module variability or the use pattern (discharge profile and average depth-of-discharge before daily charge) for which the battery was designed. The scenario just discussed describes the development and testing of the EV-1300* battery built by Globe Union for the DOE/GE Hybrid Test Vehicle (HTV-1) [1, 3].

The EV-1300 battery has been tested by Globe Union, General Electric, and NBTL. In all cases the modules tested met the battery design specifications, but significant variability between modules could be noted. As shown in Fig. 2, the variability increased markedly at high currents. Two of the EV-1300 modules were tested at NBTL using the SAE D cycle and a special cycle suggested by General Electric to simulate the HTV on the EPA urban cycle (FUDS). The results shown in Table 1 again indicate significant variability between the modules, with the variability increasing for cycles having higher pulse currents. Note that the module variability for the cycles is much greater than that corresponding to the average current for the cycle. The variability is more closely correlated with the peak current in the cycle. When a pack consisting of 10 EV-1300 modules was tested in the Hybrid Test Vehicle (HTV) on the dynamometer over the FUDS cycle, the useable A h capacity of the battery was much less than expected based either on

*The EV-1300 battery utilizes essentially the same technology, including electrolyte recirculation, as the EV-3000 and EV-2300 batteries.

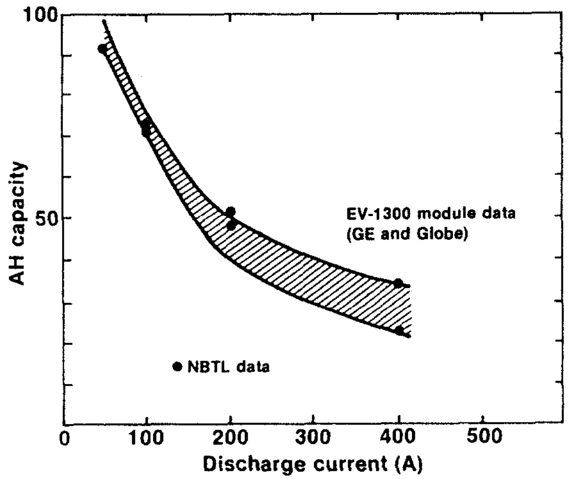

Fig. 2. EV-1300 module test data for a range of discharge currents.

TABLE 1

Pulsed profile discharge characteristics of the EV-1300 battery*

Discharge profile	Average current (A)	Peak current (A)	Time between peaks (s)	Capacity (A h)	Variability (%)	Testing group
SAE "D" simulation of ETV-1 with regen.	33	135	120	67 - 80	17	NBTL**
Special cycle to simulate the HTV on the EPA urban cycle	56	170	200	67 - 80	17	NBTL
Special cycle to simulate the HTV on the EPA urban cycle	85	255	200	47 - 61	26	NBTL
Special cycle to simulate the HTV on the EPA urban cycle	102	306	200	33 - 43	26	NBTL

*Test terminated when battery voltage drops to 1.3 V/cell during peak current pulse.
**NBTL tests two 12 V modules.

module tests at NBTL or General Electric computer simulation of the HTV [1]. A likely reason for this disappointing performance of the EV-1300 battery pack in the HTV (even when the pack was new) was the variability between modules and its effect on pack performance. No testing was done to evaluate this possibility before or after the EV-1300 battery pack was assembled.

The experiences with the HTV are not unique or unusual. Field tests of many electric cars have yielded a range and vehicle performance which is disappointing compared with expectations based on battery module tests. In addition, battery life in field tests is often found to be significantly less than expected based on laboratory module tests over regular charge/discharge cycles. These field experiences with battery packs indicate a need for group testing of battery modules over realistic discharge/charge cycles and the feedback of this information to the battery manufacturers for application in their R&D programs.

4. Conclusion

At the present time most battery testing involves single cells or modules with little attention being given to cell/module variability. Most battery pack testing is done after the battery development is completed and is often done in connection with electric vehicle evaluation. It is not uncommon for the results of pack testing in vehicles to be disappointing in terms of vehicle range and acceleration compared with that expected based on tests of single modules. In addition, the useful life of battery packs in vehicles is often considerably shorter than that expected based on life cycle tests of cells/ modules. It is likely that the disappointing experiences with battery packs is, to a significant extent, due to the variability between cells/modules which becomes greater at high discharge rates. This variability can strongly affect the performance and life of a battery pack. Little data are available concerning the variability of cells/modules and its changes during the battery aging process.

In this paper a methodology is presented for group testing of battery cells/modules utilizing computer controlled charge and discharge profiles and data acquisition and analysis. The terminal voltage and temperature of each module would be measured and stored during sampling sweeps. The voltage and temperature of the pack would also be measured before and after each sweep. A discussion is given of possible test procedures and data analysis. It is proposed that constant-current and constant-power discharges be performed to determine the standard deviation, σ, of the terminal voltage distributions as functions of current, power, and depth-of-discharge. The data would also be used to determine the Puekert and Ragone curves based on regression analysis for comparison with the corresponding curves for the pack. Relationships would be sought between the differences between the module and pack curves and the module variability as given by the standard deviations, σ. In addition, the variability in the voltage *versus* current, depth-of-discharge correlations of the modules during pulsed discharge tests would be related to that of the pack. Finally, the module variability would be related to variations in module weight and internal plate characteristics based on module teardown analyses.

Group test methodology and data analysis techniques should result, which can be used by battery manufacturers to better control their fabrication processes and be used by vehicle designers and users to permit them to more realistically evaluate vehicle performance and battery life based on module test data.

References

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