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Evaluation of lead/acid batteries under simulated electric-vehicle duty: development of design parameters on the basis of SFUDS performance

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Abstract

As manufacturers move to meet the expanding demand in batteries for electric-vehicle (EV) applications, there is a need to develop and apply test schemes that provide a true measure of battery performance. The Simplified Federal Urban Driving Schedule (SFUDS) is one of several such duty profiles that have been derived from extensive studies of urban vehicle duty. Accurate implementation of the SFUDS is, however, difficult because the load is specified in terms of power and is varied every few seconds. This necessitates a sophisticated control strategy, combined with high-speed monitoring. In our laboratories, these requirements have been met by a digital measuring and control system in which all functions are handled by a microprocessor. SFUDS testing reveals battery performance to be critically dependent on the specific power capability. In particular, maximum vehicle driving range depends primarily on the proportion of current-generating materials that are present. For optimum performance, lead/acid batteries for EV service should be designed for minimum unit weight and maximum power output. In this way, the average rate of discharge is minimized and the battery voltage remains longer above the cutoff value. From these observations, it is suggested that the next generation of EV batteries will probably resemble present-day automotive (thin plate) batteries rather than the heavier (thick plate) units that are currently used in motive-power applications. They will also need to incorporate improved negative plates which are better able to withstand repetitive high-rate cycling. The latter is the defining feature of EV duty because it places severe demands on both the positive and negative plates.

Keywords: SFUDS; Valve-regulated lead/acid batteries; Test regimes; Controlled power charge/discharge; Electric vehicles; Thin-plate

1. Introduction

Since the announcement of initiatives to promote the use of electric vehicles (EVs), there has been growing interest in developing effective methods for evaluating the batteries to be used in these vehicles. In the USA, from where much of the impetus for EV implementation has arisen, the starting point for much of this work has been the Federal Urban Driving Schedule (FUDS). The main reason for this approach is that the FUDS is a standard test regime that is used for all vehicles, including internal combustion-engined types [1]. While undoubtedly representative of vehicle duty, the FUDS is too complex to be utilized accurately in a widespread fashion. The need for a more practical test scheme was addressed several years ago by the US Department of Energy at their Idaho Laboratories. This led to the development of a simplified version of the FUDS, the 'SFUDS' [2]. The SFUDS is defined by the plot of specific power versus time given in Fig. 1.

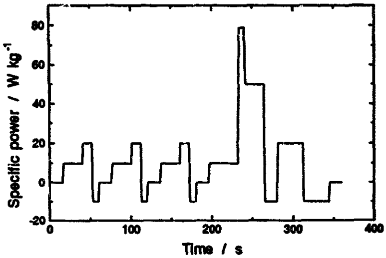

Fig. 1. Specific power–time curve for the Simplified Federal Urban Driving Schedule (SFUDS).

The SFUDS differs from test procedures that are commonly employed for lead/acid batteries in three respects. First, the load is expressed in terms of power, normally, constant current is the base parameter. Second, the magnitude of the load reaches relatively high values. Third, the total duration of the profile is brief, namely, 360 s. The study

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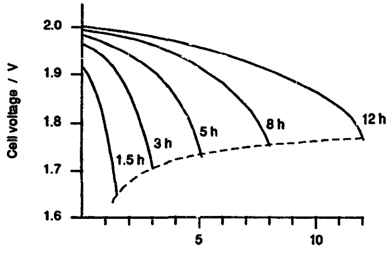

Fig. 2. Voltage–time curves for automotive lead/acid cells subjected to various given rates of discharge. The dashed line indicates the end-of-discharge voltage (after Linden [3]).

reported here is concerned mainly with the relationship between the first two features and the design of the battery. In addition, we aim to show that accurate SFUDS testing requires equipment with a high degree of sophistication.

1.1. Why test batteries at constant power?

Electric vehicle performance is determined primarily by the power available from the battery. Therefore, accurate evaluation of EV batteries should be based on schedules in which power is the control variable. Standard tests of motive-power lead/acid batteries are, however, conducted at constant current. This reflects the fact that, at low-to-moderate loads, the terminal voltage during discharge is reasonably constant and this, in turn, means that power will be reasonably steady under a constant-current load. Again, this approximation is only valid for relatively small loads, at moderate depths-of-discharge (DODs).

Of course, the terminal voltage of a cell/battery decreases during discharge and, as shown in Fig. 2, this decrease becomes greater, and more sensitive to DOD, as the current (load) is raised [3]. In order to meet the power demands throughout discharge, any fall in voltage must be matched by an increase in the current drawn from the battery. The SFUDS includes periods of relatively high specific power (up to 79 W kg^{-1}). As will be shown later, for certain types of battery, such loads are comparable with the cranking rate in automotive applications. Moreover, at these high rates, constant current does not approximate to constant power and, therefore, power must be the principal control parameter.

1.2. A closer look at the SFUDS

According to the literature available on the implementation of SFUDS [2], cells/batteries for testing are subjected to consecutive iterations of the load profile (Fig. 1) until one of three criteria is met: (i) the unit cannot provide 50 W kg^{-1} when it is demanded during the 79 or 50 W kg^{-1} stages of the profile; (ii) the unit cannot deliver the power required at any other stage of the schedule, and (iii) the unit cannot operate at, or above, certain imposed conditions, such as minimum (cutoff) voltage under load. In the study reported here, we have found that the end-of-cycle is always determined by condition (iii). At that point, the cell/battery is returned to 100% state-of-charge (SOC), according to the manufacturer's instructions, and is said to have completed one SFUDS cycle.

In completing one SFUDS cycle, the cell/battery makes N passes through the SFUDS profile. We define each of these passes through the profile as a 'sub-cycle'. With each sub-cycle, there is a net discharge of 0.987 Wh kg^{-1} (total discharge is 1.187 Wh kg^{-1}, total charge (simulated regenerative braking) is 0.2 Wh kg^{-1}). Hence, the terminal voltage falls progressively, until it reaches the lowest allowable value (set by the manufacturer). In order to illustrate how cell/battery performance changes during SFUDS duty, it is helpful to plot the lowest voltage registered during each sub-cycle versus the number of sub-cycles. We have found that the lowest voltage occurs during the 8 s period of maximum load (79 W kg^{-1}). Fig. 3 provides an idealized version of such a plot for three successive SFUDS cycles.

In seeking to quantify the performance of a cell/battery under the SFUDS, we define the total (cumulative) discharge during one cycle (N sub-cycles) as the 'SFUDS capacity'. The average of this quantity over the first three cycles is the 'useful capacity', in line with the practice adopted for other test schedules [4]. This is the capacity that is available between charging periods and, therefore, provides a direct indication of the driving range of the vehicle. Consequently, a true evaluation of the performance of a particular cell/battery must consider: (i) the useful capacity, and (ii) the number of SFUDS cycles to end-of-life, e.g. 80% of initial capacity. In this study, we aim to investigate the ways in which the basic design of the cell/battery influences the simulated on-road performance of an EV, via its effect on the useful capacity. To do this, two distinctly different types of valve-regulated lead/acid (VRLA) cell/battery are examined. One is similar in plate design to the majority of units

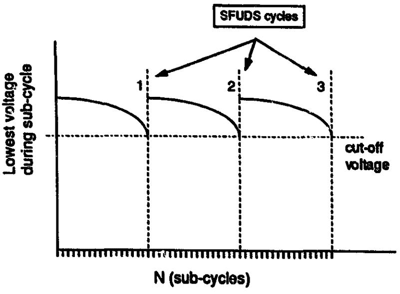

Fig. 3. Idealized representation of relationship between SFUDS cycles and sub-cycles.

produced for traditional EVs, (e.g., golf carts) in that it features relatively thick plates. The other unit is constructed from thinner plates and resembles, to some extent, an automotive battery.

2. Experimental

Controlled-power testing regimes like the SFUDS are more difficult to implement than conventional constant-current regimes because power cannot be measured directly. Rather, to measure the power load on a cell/battery, both the voltage across the load and the current through the load must be measured. Power is the product of these two parameters and is regulated by varying the voltage and/or the current. As voltage control of batteries is neither practical nor applicable for EV applications, the required power is set by adjusting the current.

Another way of conducting this type of testing is to assume an average battery voltage and then meet each of the constant-power steps by setting the current. Such a strategy, however, constitutes a poor approximation to true constant-power duty. Most importantly, the actual load only matches the required load when the terminal voltage equals the assumed average value. As will be shown later, values of the terminal voltage recorded during SFUDS duty span a considerable range. Therefore, for most of the test schedule, the cell/battery will be subjected to a load that differs appreciably from that required. The result of these differences is that the important correspondence between duty under the laboratory test schedule and actual duty in the vehicle is probably lost.

In our laboratories, the SFUDS is implemented by means of a digital measuring and control system, at the heart of which is a microprocessor-based controller. A block-diagram of the equipment is provided in Fig. 4. Charging/discharging of the cell/battery is carried out by the power stage, in accordance with a set of control and measurement parameters that comprise the required duty profile. The profile is programmed from a host computer, via the network interface (standard Ethernet). The controller: (i) monitors both the current flow, by means of a current shunt, and the terminal voltage of the cell/battery; (ii) calculates the power; (iii) compares the value from (ii) with that required by the profile, and (iv) adjusts current and/or voltage via the control output.

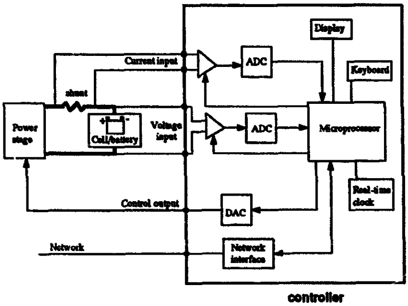

Fig. 4. Block diagram of internal functions of the controller and its connections to the power stage and cell/battery under test.

The controller only has direct control over the current flow from the power stage. Therefore, voltage and power are set indirectly by feedback control of the current. Successful operation of the feedback system requires the controller to operate at reasonably high speeds. In the case of the SFUDS, the controller makes any necessary adjustments to the current every 4 ms. The controller also functions as a data logger and records a set of measurements at intervals in the range of 4 ms to several hours. These measurements are transmitted back to the host computer. The speed of operation allows accurate recording of instantaneous voltage, current, power and energy which, in turn, ensures that the SFUDS (or any other load profile) is followed accurately. The control system also terminates the SFUDS cycle when one of the end-of-cycle criteria is met, e.g. battery voltage drops below a predetermined value. The battery is then charged and testing continues.

The controller has been equipped with an internal real-time clock, a liquid crystal display, and a keyboard. These features allow, amongst other things, operation as a stand-alone charge/discharge controller that is capable of storing a range of simple profiles in the microprocessor. The controller can perform a wide variety of tasks that range from short-pulse to extended-period profiles. The software control allows constant/pulsed current, constant/pulsed voltage, or constant pulsed/power charging and discharging. Each charge or discharge step can be either switched to other charge/discharge conditions or terminated by: (i) time; (ii) current or voltage; (iii) overcharge factor; (iv) temperature or pressure; (v) internal resistance, and (vi) power. It is also possible to combine logically all these conditions.

Two types of lead/acid cell/battery are examined in this study, unit A and unit B. Both are valve-regulated types in which the electrolyte is immobilized in absorptive glass microfibre (AGM) mat. Details of the construction of units A and B are summarized in Table 1. Charging was conducted at a constant current of 60 A until the terminal voltage reached 2.45 V/cell. Each unit was then held at this voltage until the required amount of overcharge had been supplied. On average, both units received between 10 and 15% overcharge. Repetitive charge/discharge cycling was conducted at $C_3/3$ (3 to 5 cycles) in order to establish constant capacity. The values of C_3 are collected in Table 2.

The experimental procedure for SFUDS evaluation is as follows:

(i) subject the cell/battery to repetitive SFUDS sub-cycles at room temperature (~20 °C) until the battery fails to meet one of the performance criteria (*v.s.*); record the total capacity;

Table 1
Construction details of units A and B

Weight (kg)		Plate dimensions (mm)			Active material per plate [a] (g)	No. plates per cell	Active material ratio [a] (N:P)	Total active materials per unit [a] (%)
		width	height	thickness				
a) *Unit A* (12 V)								
10.25	P [b]	160	90	1.1	74.7	5	1.02:1	44
	N [c]	160	90	0.8	63.7	6		
b) *Unit B* (2 V)								
7.75	P [b]	184	141	3.0	198.6	5	1.26:1	29
	N [c]	184	141	2.5	209.3	6		

[a] Weight of active materials is given in terms of the equivalent weight of lead.
[b] P = positive plate.
[c] N = negative plate.

Table 2
Discharge performance of test units [a]

Unit	Weight (kg)	Cycle No.	No. sub-cycles	SFUDS capacity [b] (Ah)	Useful capacity per cell [c] (Ah kg^{-1})	C_3 per cell (Ah kg^{-1})
A	10.25	1	23	20.2	12.6	14.6
		2	25	21.8		
		3	26	22.6		
B	7.75	1	15	56.8	7.4	12.8
		2	16	60.1		
		3	15	56.1		

[a] Cutoff voltage: 1.7 V.
[b] Cumulative discharged capacity for complete SFUDS cycle.
[c] Useful capacity = average SFUDS capacity for cycles 1 to 3.

(ii) allow the cell/battery to stand at open circuit until the temperature falls to 30 °C; note, selection of this value of temperature (and in (iv), below) is an in-house decision;

(iii) recharge the cell/battery, to a given overcharge factor, as recommended by the manufacturer;

(iv) allow the temperature of the cell/battery to fall to 30 °C;

(v) repeat steps (ii) to (v).

It should be noted that for both unit A and unit B, the termination of SFUDS cycling occurred when the voltage fell to the cutoff value (stipulated by the manufacturer). In establishing this important fact, we considered the possibility that the highest currents required to follow the SFUDS might exceed the capability of the power stage. This would have limited the power to a value less than that demanded by the schedule. In fact, we found that the current-sinking capability of the charge/discharge control system was, in all cases, considerably greater than the peak load current drawn from either of the units examined. Therefore, we were able to implement the SFUDS with complete accuracy.

3. Results and discussion

Fig. 5 presents a summary of the changes in voltage and current that were recorded for unit A during the first SFUDS cycle. The traces for both the current and the voltage deviate sharply during the period of peak load (79 W kg^{-1}). In this period, the current reaches its highest value while the voltage falls to its lowest level. Further, with each successive sub-cycle, the average voltage follows a downward trend. In a corresponding fashion, the discharge current increases, though the changes are less obvious. A plot of the minimum sub-cycle voltage against sub-cycle number gives a smooth curve, similar to that provided in Fig. 3. Unit A completed 23 sub-cycles before the terminal voltage fell, near the end of the peak-load period, to the cutoff value (10.2 V, 1.7 V/

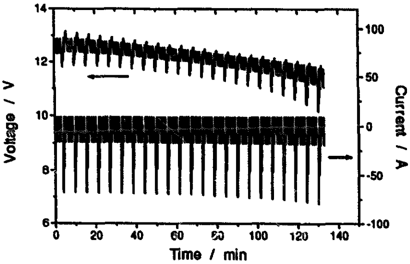

Fig. 5. Plots of voltage and current vs. time for unit A during SFUDS cycle No.1; cutoff voltage is 1.7 V/cell.

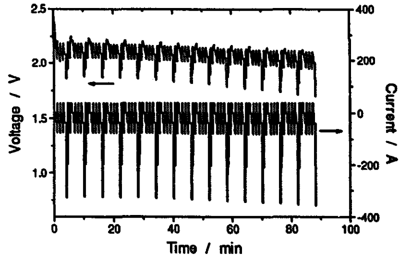

Fig. 6. Plots of voltage and current vs. time for unit B during SFUDS cycle No. 1; cutoff voltage is 1.7 V/cell.

cell). The corresponding data set for unit B is given in Fig. 6. This cell completed significantly fewer sub-cycles (viz., 15 versus 23) before the voltage fell to the same cutoff value (1.7 V/cell), also during operation at peak load.

A total of three SFUDS cycles was conducted on each battery. As shown in Table 2, the number of sub-cycles completed and, hence, the capacity available on each cycle, was virtually constant. From these data, the useful capacities per cell were calculated to be 12.6 and 7.4 Ah kg^{-1} for units A and B, respectively. Therefore, the same vehicle fitted with equal weight of either unit would be able to travel ~70% further when powered by unit A as opposed to unit B. In addition, we note from Table 2 that the comparison of C_3 data gives no real indication of the superior performance of unit A; the specific capacity per cell of unit B at $C_3/3$ is only slightly lower than that for unit A.

As noted above, the useful capacity represents the distance that can be travelled between stops for recharging of the battery. Despite the obvious importance of this parameter, however, neither the US Advanced Battery Consortium nor the Advanced Lead–Acid Battery Consortium has set a target value. Instead, they specify that a battery must complete a minimum number of SFUDS cycles while its useful capacity remains above 80% of the initially determined value. While the number of complete cycles is certainly an important variable, it does not define the total, i.e., lifetime, driving distance delivered by the cell/battery. In the present case, let us suppose that units A and B were both subjected to continued SFUDS duty and that they delivered the same number of cycles prior to removal from service. In such a situation, a vehicle fitted with unit A would have been expected to cover a total service distance that was ~70% greater than that covered by the same vehicle fitted with the same weight of unit B [1].

The other way of viewing this comparison is to consider the same type of EV, fitted with different numbers of either unit A or B, where the aim is to obtain the same driving range.

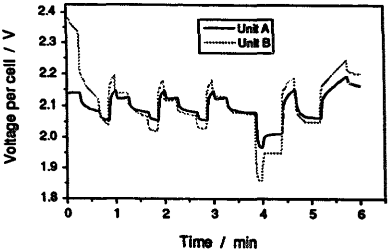

Fig. 7. Plots of voltage per cell vs. time for units A and B during the first SFUDS sub-cycle; cutoff voltage is 1.7 V/cell.

The first attempt at achieving this would be to specify a greater weight of the battery based on unit B, because of the lower useful capacity (Table 2). As a result, the vehicle fitted with unit B will: (i) need a much larger battery compartment, and (ii) weigh more than the vehicle with a battery based on unit A. In fact, though, the weight of battery B will need to be greater than the predicted value. This is because the vehicle fitted with unit B is now considerably heavier than that fitted with unit A. With no allowance made for this weight difference, the former will have a lower driving range. Clearly, the useful capacity of an EV cell/battery is a crucial factor in determining the acceptability of battery-powered vehicles.

In order to explain the marked difference in behaviour for units A and B, we now take a closer look at Figs. 5 and 6. Comparison reveals that the terminal voltage of unit A remains higher, relative to the cutoff value, than does the voltage of unit B. This is highlighted by plotting cell voltage–time curves for the two units on the same set of axes. Fig. 7 provides an example of such a plot, for the first sub-cycle, i.e. both batteries commence in the fully charged state. Although the terminal voltage of unit B begins at a higher value than that of unit A, the former quickly falls to below the latter during the first period of discharge. From that point, the voltage of B is always lower than that of A on discharge, and always higher than A on charge.

It should also be appreciated that the behaviour of unit B in this test is, in fact, somewhat 'ideal'. This is because B is a 2 V cell and, consequently, its performance is not diminished by any resistive losses due to the inter-cell connections that are present in all battery systems. Although unit A suffers such losses, its performance still easily surpasses that of unit B under SFUDS cycling. As will be shown in subsequent discussion, the principal reason for this difference in charge/discharge behaviour is the fact that the relative rates of charge and discharge, i.e., per unit mass of active materials, are considerably higher for unit B than for unit A.

3.1. *Cell/battery design parameters for maximizing EV performance*

Given that SFUDS loads are expressed per unit weight of cell/battery, the weight of the non-current-generating com-

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[1] We assume here that the useful capacity of both units falls at approximately the same rate, to the 80% end-point.

ponents is obviously important. Among these, the most significant components are those made of lead, i.e. the grids, bus-bars, inter-cell connections, posts and terminals. Table 1 includes a breakdown of the component weights in A and B. According to the calculated mass ratio of the total active materials (as Pb) and the complete cell/battery, a significantly larger portion of unit A contributes to energy conversion than in unit B. This fact largely defines the superior performance of the former unit under the SFUDS. The key effect here is that, per unit weight of cell/battery, B is subjected to a higher rate of discharge than A. Consequently, the terminal voltage of the former will always be lower during discharge. This behaviour is well illustrated by the comparison of voltage–time curves provided in Fig. 7.

Another factor that should be considered is the relative amounts of positive (P) and negative (N) active-materials. This is a complex topic because the mass ratio of materials (N:P) affects several fundamental properties of the lead/acid cell. Perhaps the most important issue here, though, is the effect of the ratio on the performance at high rates of discharge. More particularly, it is known that the amount of negative active-material usually determines the ability to sustain high loads, e.g. cranking currents in automotive applications. The reason for this dependence is that discharge at high rates only utilizes a thin surface layer of plate material. Therefore, the total surface area of plate materials limits the performance. Given that the specific surface area of the negative material is always much less than that of the positive component, i.e. 2–3 versus 6–8 $m^2 g^{-1}$ [5]), the polarization of the negative plate will increase before that of the positive plate because the surface of the negative material will be covered by $PbSO_4$ before the positive. Moreover, increasing the current load enhances the bias of polarization towards the negative plate. This, in turn, means that most of the fall in the cell voltage during high-rate discharge will be due to the fall in the negative-plate voltage. The cell is then said to be 'negative limited'.

It is interesting to note that unit B is actually constructed with a greater proportion of negative-plate material than unit A (Table 2). In spite of this, the performance of B is inferior. This indicates that it is the ratio of current-generating materials to the total cell/battery weight combined with the relative thickness of plates, that exerts a dominant effect on SFUDS performance. Any changes in the N:P ratio are of less importance. Nevertheless, some caution is required in describing the performance of unit B as inferior, because, as pointed out earlier, the total service time provided by an EV battery is a function of both the number of sub-cycles and the number of complete cycles. While unit B clearly scores poorly in the former category, it may eclipse unit A in the latter. In this respect, it is likely that the relatively high proportion of negative-plate material in unit B will have a beneficial effect.

Support for the idea of providing EV batteries with a greater proportion of negative material can be found in one of the few detailed accounts of failure modes of lead/acid batteries subjected to SFUDS life-cycle testing [6]. That work reported on the performance of typical 6 V (gelled-electrolyte) batteries. The results showed that failure, as signalled by a fall of capacity to 80% of the initial value, was due to degradation of the negative plates. It was found that considerable 'densification' of the negative active-material had occurred. This was confirmed by measurements of specific pore volume which showed a significant drop in porosity. Given that the N:P ratio of plate materials in the test unit was 1.08:1, it is reasonable to conclude that a cell/battery with relatively more negative-plate material would have yielded longer service under the same conditions.

Both the proportion of negative-plate material and the fraction of materials that participate in the energy-conversion reactions become less important as the rate of discharge is lowered. This places constraints on the way in which batteries are rated for EV service. In particular, it is not possible to compare meaningfully two different EV batteries on the basis of their capacity at, for instance, $C_3/3$. From earlier discussion, values of C_3 for units A and B were found to be similar and, therefore, they provided no indication of the difference in performance under simulated EV duty.

A comparison of the values for C_3 and the useful capacity (Table 2) does suggest, however, that a similarity in these two capacities, as obtained for unit A, can be used as a measure of suitability for EV duty. In this regard, we note that dividing the net discharge per SFUDS sub-cycle by the cycle period (6 min) yields an 'overall' rate of discharge that is close to $C_3/3$ (cf., SFUDS overall with $C_3/3$: 8.7 A and 8.3 A for unit A; 37.6 A and 33.0 A for unit B). If cell polarization is determined by the fall in voltage of the positive plate, as is normal with constant-current discharge at $C_3/3$, then the useful capacity of the cell/battery should be close to C_3. For unit A, this is clearly true and, as a result, the battery performs well under the SFUDS. For unit B, cell polarization throughout most of the SFUDS is determined by the negative-plate voltage. Consequently, the useful capacity is considerably lower than C_3 and SFUDS performance is poor.

Based on the above data, we suggest that a certain ratio of the useful capacity to C_3 could serve as an effective criterion for assessing the driving range of an EV.

3.2. *Key design criteria for electric-vehicle batteries*

From this analysis of the behaviour of two different types of lead/acid cell/battery, it is clear that several features should be included in the design of a successful EV battery. The fundamental requirement is that the cell/battery must be able to sustain a relatively high rate of discharge. Such high-rate ability is achievable through: (i) a high ratio of active-material weight to total cell/battery weight, and (ii) a larger number of thinner plates. In fact, the general philosophy is similar to that applied by battery manufacturers in the design of automotive batteries. The high-load ability of such batteries is needed for good cold-cranking performance. In this regard, we suggest that EV batteries should also include other features that are known to minimize the decline in terminal voltage during high-rate discharge. For example:

- grids of radial rather than rectilinear configuration
- improved separators of lower resistivity
- sufficient acid for good electrolyte conductivity

This raises another important issue that is related to electrolyte. Safety requirements for EVs demand that the electrolytes used in batteries be immobilized to a large extent. This limits the release of electrolyte in situations where a cell/battery case is ruptured, e.g. as a result of an accident or collision. For lead/acid, VRLA technology meets this important criterion. In this work, units A and B both utilize absorptive glass microfibre as the medium for immobilizing the electrolyte. In earlier discussion, it was noted that the balance of active materials in a lead/acid cell influences the discharge performance. For VRLA cells, the relative amounts of materials also influences the efficiency with which oxygen is 'recombined' within the cell. This important property must be carefully optimized in an EV battery. Certainly, recombination is enhanced by a high negative-to-positive mass ratio. This feature should also lower the rate of decrease in negative potential during high-rate discharge. Yet, as we have seen in the case of unit B, simply providing an excess of negative material, regardless of other factors, does not lead to good SFUDS performance.

4. Concluding remarks

In conducting this investigation of simulated EV duty, it has become clear that accurate evaluation of a cell/battery according to the SFUDS regime is far from straightforward. In order to ensure that the cell/battery follows closely the load required by the schedule, a sophisticated control strategy is needed. The latter combines high-speed monitoring with rapid, continual adjustment of control parameters. Such an approach is especially important as the cell battery approaches the end of discharge. In this phase of operation, the terminal voltage begins to fall rapidly, to significantly lower values. The control system must be able to make adjustments to the load current quickly, so that the specified power is always being drawn.

The performance of a cell/battery under the SFUDS is critically dependent on the specific power capability of the unit. This, in turn, is determined principally by the proportion of cell/battery weight that is dedicated to the active materials, i.e. the current-generating fraction of the unit. For maximum EV driving range, battery design should aim for the dual target of minimum unit weight and maximum power output. In this way, the average rate of discharge is minimized and the battery voltage is maintained longer above the cutoff value.

In practice, these requirements can be met by specifying thinner plates and minimizing resistive losses. The former poses challenges to existing technology — grid manufacture, plate processing and cell assembly must all be optimized to obtain good high-rate cycleability. In particular, we have seen that negative-plate cycleability may become the life-limiting factor in EV duty. This indicates that a renewed research effort in the area of additives for negative material is required.

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