
Development of Optimized Fast Charge Algorithms for Lead Acid Batteries

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ABSTRACT

Recent studies have demonstrated that fast charging techniques can significantly extend the effective daily range of lead acid battery powered EVs. Further, other research has shown that the total lifetime energy delivery of suitable VRLA batteries can be increased markedly through partial state of charge cycling. A research team composed of Arizona Public Service (APS), CSIRO Division of Minerals (CSIRO), Electric Transportation Applications (ETA), and Hawker Energy Products, Incorporated (HEPi) has been assembled to conduct a detailed laboratory and field program to develop operating regimes that will improve lead acid battery performance in EV applications using fast charge and PSOC operation. Research is being conducted under the cognizance of the Advanced Lead Acid Battery Consortium, both in the laboratories of CSIRO and HEPi, and in the electric vehicle fleet of APS and ETA.

Initial field testing of Hawker Genesis[®] 12 volt, 38 Ah modules in a US Electricar S 10 pick up truck has provided very encouraging results. The vehicle was charged using a 150 kW Norvik Mini[®] Charger at a maximum current of 165 amperes (5C at the 33 Ah C₁ rate for the Hawker Genesis[®] modules). The vehicle was operated three to four cycles per day from about 20% to about 80% SOC. The battery pack delivered a total of 15,258 Ah (462 times the 1C rate) in accumulating 16,846 miles on the S10 test vehicle. Initial laboratory testing has focused on maximum charge rates and the temperature effects of hyper-charging (rates greater than 9C) lead acid batteries. Charge rates of 29C were found to fully charge Hawker Genesis[®] 12 volt, 13 Ah modules. However, the highest practical upper charge limit was 11C, as

temperature effects presented an upper limit on practical fast charge rates. Preliminary testing has shown the combination of fast charging and partial state of charge operation in EV batteries to be very promising in terms of increasing both cycle-life and effective vehicle range.

This paper details the results of initial project testing and concludes that temperature effects present an upper limit on fast charge rates and that preliminary testing indicates very beneficial results are obtained by the combination of fast charging and partial state of charge operation in EV batteries.

INTRODUCTION

Recent studies have demonstrated that fast charging techniques can significantly extend the effective daily range of lead acid battery powered EVs. Further, other research has shown that the total lifetime energy delivery of suitable VRLA batteries can be increased markedly through partial state of charge cycling. A research team composed of Arizona Public Service (APS), CSIRO Division of Minerals (CSIRO), Electric Transportation Applications (ETA), and Hawker Energy Products, Incorporated (HEPi) has been assembled to conduct a detailed laboratory and field program to develop operating regimes that will improve lead acid battery performance in EV applications using fast charge and PSOC operation. Research is being conducted under the cognizance of the Advanced Lead Acid Battery Consortium, both in the laboratories of CSIRO and HEPi, and in the electric vehicle fleet of APS and ETA.

Initial work by the research team has focused on establishing upper bounds for charge rate and equalization fre-

quency using both laboratory and field testing. The results of this initial testing are reported herein.

BACKGROUND

Fast charging has demonstrated promise in overcoming the limited range of EVs powered by lead acid batteries. With such an approach, EVs can be 'refueled' several times a day. Fast charging is ideally suited to vehicles that can return to a central fueling point during the day (e.g. fleet vehicles and buses). With central fueling, one sophisticated fast charge station can serve many vehicles. This increases both the utilization and the load factor of the station.

Initial studies involving the fast charging of lead acid batteries have shown that significant range extension can be obtained. EVs using charge rates from 3 to 9C have achieved ranges of over 120 miles per day [1]. Conclusions from these studies and other investigations are as follows:

- Excessive equalization can cause accelerated grid corrosion resulting in premature failure [2]
- Low power charging can result in undercharging and a subsequent reduction in VRLA battery capacity [3]
- Fast charging does not reduce battery life if battery temperature is maintained at a reasonable level; in some circumstances it may even extend life [4]
- Temperature rise from ohmic heating and recombination during fast charge may limit the frequency of charging [5]
- Charge rates in excess of 5C can be successfully applied to laboratory VRLA batteries [6]

Studies by CSIRO have further demonstrated that partial state of charge (PSOC) operation [7] can offer remarkable improvements in the performance of VRLA batteries that are not prone to acid stratification. Using a PSOC charge schedule with a gelled electrolyte battery, energy delivered over the battery life (presented in Table 1) in CSIRO testing was found to be approximately three times greater than that obtained under traditional cycling conditions to the same depth of discharge. PSOC duty also resulted in remarkable improvements in charge efficiency.

The improvement in the total lifetime energy delivery under PSOC duty is attributed mainly to the decrease in overcharge. This reduction decreases both the gassing during charging and positive grid corrosion. Thus, water losses due to both escape from the battery and grid corrosion are decreased. In addition, as PSOC operates the batteries below the gassing region, cell imbalances due to differing degrees of recombination are minimized.

With the benefits of both fast charging and partial state of charge operation demonstrated in EV batteries, it is logical to combine the two methodologies and determine whether synergistic effects exist in terms of greater EV range and longer battery life. This combination was

recently investigated by Cominco [8]. They operated an electric G-van under PSOC (~20 to 80% SOC) and fast charging conditions. The results indicated that cycle life can at least be maintained and that multiple charge/discharge cycles per day can be performed. Although these results are promising, the SOC operating window and the number of partial cycles between full recharges have not been optimized with respect to the charging rate. For example, as charge rates increase, full recharges may be required more frequently given that charging efficiency decreases with increasing charge rate. Additionally, the practicality of using a smaller portion of battery capacity (e.g. 20% SOC to 80% SOC) has not been evaluated in a field situation.

Table 1. Energy Delivery of Batteries Operated Under Traditional And PSOC Conditions

Operating Regime	Number of Cycles	Total Energy (Ah)	Multiples Of C ₁ Rate*
100% SOC to 90% SOC	6000	86,000	600
100% SOC to 80% SOC	3200	91,500	640
100% SOC to 60% SOC	1250	71,500	500
100% SOC to 40% SOC	900	77,000	540
100% SOC to 20% SOC	700	80,000	560
100% SOC to 0% SOC	500	71,000	500
PSOC 40 to 70% SOC	5500	235,950	1,650

* Battery capacity equals 143 Ah

If lead acid batteries are to capture a major share of the EV battery market, the perceived range and cycle life limitations associated with lead acid technology must be overcome. The combination of fast charging and PSOC operation offers a potential solution to this problem. To investigate this possibility, an integrated laboratory and field program was initiated in conjunction with the Advanced Lead Acid Battery Consortium (ALABC) to develop and demonstrate advanced operating schedules for lead acid powered EVs.

RESULTS

FIELD DEMONSTRATION @ 5C

Vehicle configuration – An initial field demonstration was conducted using APS Vehicle #3333, a US Electricar S10 pick up truck. The traction battery in this vehicle operates at 312 volts. The vehicle normally uses two strings of 26, twelve volt modules. For this field demonstration it was configured with a single string of 28 Hawker Genesis[®] 12

volt, 38 Ah modules. This modification allowed charge current at the 5C level to remain within the capability of the vehicle wiring. Air cooling was supplied to the modules by a low head fan mounted at the top of the battery box and space provided around the battery pack to allow air circulation. The fan was operated during charge and for approximately 30 minutes after charge.

Charge algorithm – The charge algorithm for Vehicle #3333 was chosen based on past experience with fast charging of Hawker Genesis[®] 12 volt, 38 Ah modules [9]. No laboratory cycling was conducted prior to the algorithm selection. The algorithm was designed to conservatively provide a full charge every three to four PSOC cycles and to equalize every twelve to fifteen PSOC cycles. Previous experience indicated that this frequency would clearly be high enough to prevent run down of the battery capacity and capacity deviations between modules. The algorithm, therefore, provides a conservative lower bound on cycle life as less frequent capacity recovery (full charges) and equalization should reduce grid corrosion and extend battery life, if it can be accomplished without experiencing a run down in battery capacity. The US Electricar S 10 pickup is shown in Figure 1. The vehicle was placed into service in April, 1997.

Vehicle #3333 was charged using a 150 kW Norvik Mini[®] Charger. The 5C charge rate was based on a 33 Ah C₁ rating of the Genesis[®] module, or 165 amperes. The vehicle was operated three to four cycles per day. The first cycle of the day discharged the battery 26 Ah (about 80% DOD). The battery was then charged and discharged on a 20 Ah cycle (about 20% to 80% DOD) for the remaining cycles of the day. On the last charge of the day, the charger was allowed to return the battery to 100% SOC. Every fourth day the battery was equalized at a constant-current of 6 amperes (voltage limited to 2.45 volts/cell) for one hour. A typical daily operating cycle is presented in Figure 2.



Figure 1. US Electricar Vehicle #3333 - 5C Test Vehicle

Operating history – Vehicle #3333 was operated in accordance with a written procedure by a dedicated driver. The

driver limited discharge rates to those the module string would normally experience in a two string parallel operation. The driver also conducted all vehicle charging and logging of data to assure consistency. The vehicle was operated within metropolitan Phoenix, Arizona. Battery temperature was limited to 55°C, based on Hawker recommendations.

Vehicle #3333 was driven 16,846 miles using the Hawker Genesis[®] 12V38Ah10EP modules. The modules received 697 cycles at 5C and 738 cycles in total. End of pack life was declared based on a loss of capacity in the final modules analyzed using the predictive techniques developed in previous work conducted by ETA and APS [10] and detailed below. The vehicle range of approximately 25 miles (based on one rather than the normal two strings of batteries operational) was not impacted by loss of capacity in high cycle number modules, as several new modules had been added to the pack to replace those removed for predictive analysis. The greater capacity of these module compensated for the capacity loss in the high cycle number modules and maintained the vehicle range.

Battery performance evaluation – The battery in Vehicle #3333 delivered 15,258 Ah over the life of the pack. This is equivalent to 462 times the one hour rate for the module. No module failures were experienced over the life of the battery pack. During the pack life 13 modules were removed for internal examination and predictive analysis. Modules were selected for analysis at approximately 100 cycle intervals.

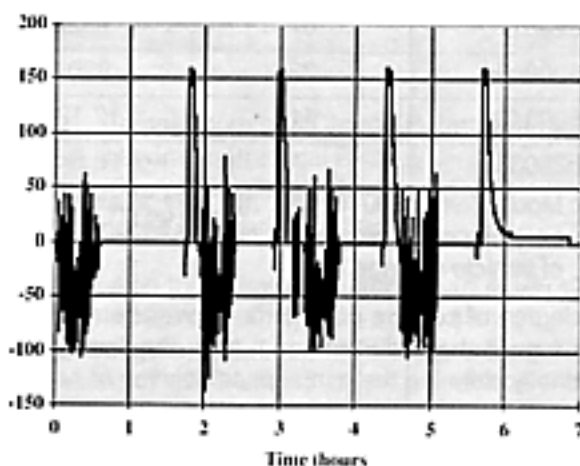


Figure 2. Typical Operating Cycle - 5C Test Vehicle (amps vs time)

The 5C charge cycle with PSOC operation (20% to 80%) allowed the vehicle to take on a PSOC charge in approximately 8 minutes. The full charge provided at the end of each working day required approximately 15 minutes. The charge algorithm allowed multiple charge cycles to be accomplished in a typical workday, effectively extending the vehicle range, even though the range per charge

was reduced by partial state of charge operation. Operated in a continuous charge/discharge mode, the battery pack required air cooling in the high ambient temperature environment of Phoenix. However, in a cold environment, this heating may be beneficial in maintaining proper battery temperature.

The algorithm proved to be effective in extending vehicle range. The eight minute charge time was acceptable, but at the upper bound of acceptability. A six minute charge time would be more acceptable in operations. The overnight requirement for a full charge was not an impediment to vehicle operation as it was only operated one shift per day. In shift operations, however, this could be a problem.

Predictive analysis – Seven modules from Vehicle #3333, at different mileage intervals, were returned to HEPi for analysis. In total, thirteen modules were removed from to ensure backup modules were available, if required, for testing. For modules analyzed, the module details and vehicle mileage at which point they were removed are presented in Table 2.

Table 2. Module Operating History

Module Batch Number	Vehicle Module Number	Vehicle Mileage At Removal
963520012	20	2217
963520018	03	2217
963520016	16	3883
963520011	09	5929
963520003	23	9904
963520040	11	12,129
963520033	7	16,846

Note: Module 963520018 was not fully analyzed internally since it replicated module 963520012 in terms of vehicle mileage.

The degree of positive grid corrosion was determined by removing all the active material from the positive grids and briefly cleaning them in a dilute solution of nitric acid and hydrogen peroxide until no further evidence of active material is present. Care was taken not to dissolve the grid during the cleaning procedure. Next, the cleaned grid was weighed and dimensionally measured for thickness and vertical wire width. Percent corrosion was determined by comparing these measurements to the starting "fresh" specifications for as-formed grid. The positive grid corrosion for each module is presented in Table 3 and Figure 3.

Table 3. Positive Grid Corrosion

Module Batch Number	Mileage	% Grid Corrosion (Vertical Wire)	% Grid Corrosion (Weight Loss)
As-formed	0	0	0
963520012	2217	8	8
963520016	3883	13	13
963520011	5929	16	16
963520003	9904	26	26
963520040	12129	24	28
963520033	16846	21	36

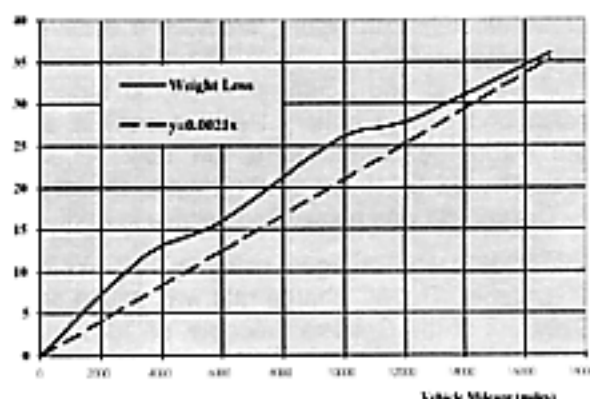


Figure 3. Positive Grid Corrosion During Life

It can be observed from the above figure that there exists a strong correlation between percent positive grid corrosion, as determined by weight loss, and battery life (vehicle mileage). This is in good accord with previous work [11] that shows a similar correlation between percent grid corrosion and cycle life. Furthermore, it has been demonstrated that end of life is reached when the positive grid has corroded by 35-40% of its original mass.

Assuming end of life to occur when the positive grid has corroded by as much as 40% of its original mass, then by using the Figure 3, the vehicle mileage to this point would be approximately 18,000 miles. It should be noted, however, that this relationship is only relevant to the recharge and temperature conditions experienced by the batteries within this vehicle.

MAXIMUM CHARGE RATE – With the objective of this project to develop fast charging algorithms that can be used in conjunction with PSOC operation, it is useful to determine the maximum rate at which state of the art AGM batteries can be charged. The absolute maximum charging rate and the maximum practical charging rate of Hawker Genesis® batteries were determined in laboratory testing.

The absolute maximum charge rate represents the maximum current that can be delivered to a battery without inducing immediate thermal runaway. It is not, however, considered practical for long term operation due to the high internal temperatures generated within the battery. The maximum practical charging rate is considered to be the fastest that a battery should be charged without unduly affecting cycle life and operational safety. This charging rate is considered suitable for short to medium term operation and is associated with moderate to high temperature increases.

The maximum charge current that could be delivered to a Hawker Genesis[®] G12V13Ah10EP (13 Ah) battery was found to be about 290 A, when charged with a resistance free voltage limit of 2.65 volts/cell. This corresponds to a charge rate of 29 C. At this current, a charge return of 0 to 80% and 0 to 100% was achieved in about 80 and 100 seconds, respectively as shown in Figure 4. A charge return of 120% was achieved after 120 seconds. It should be noted that larger G12V38Ah10EP (38 Ah) batteries are used in field tests. The smaller capacity battery was used in absolute maximum charge rate experiments due to a current limitation of 400 A associated with charging hardware.

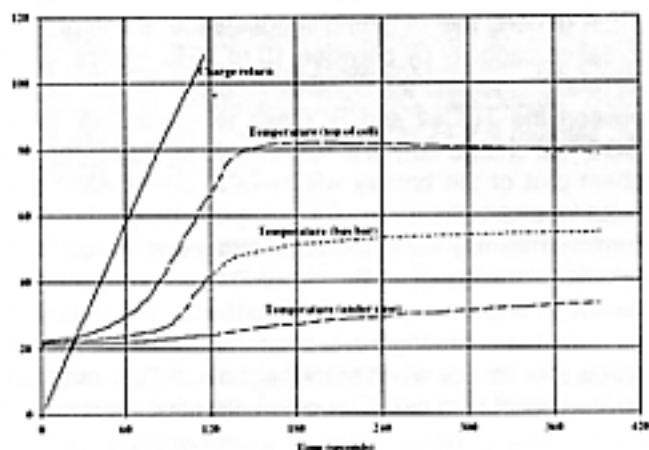


Figure 4. Charge Return and Temperature During Maximum Charge Rate Testing of Hawker Genesis[®] G12V13Ah10EP

Temperature was monitored internally at both the top of the plate group (TOCell), the busbar (BUS), and externally at the bottom of the battery case (BOCase). Initially, the temperature was also measured inside the battery at the bottom of the plate group. This temperature, however, was found to behave similarly to the BOCase temperature and, as the latter is more convenient to measure, it is assumed that the BOCase temperature is representative of the internal temperature at the bottom of the cell group.

The BUS and the BOCase temperatures increased from about 22°C to 25°C and 23°C, to 41°C and 25°C, respectively, (Figure 4) after 100% and 120% charge return. By contrast, the rate of temperature increase at the top of the cell (RTOCell) was higher than that at the busbar

(RBUS) or the bottom of the case (RBOCase). For example, the TOCell temperature had increased from 22°C to about 60°C after 100% charge return, with a maximum of 80°C being reached some 30 seconds after the completion of charging (120% charge return). Interestingly, the BUS and BOCase temperatures continued to rise after the TOCell had stabilized. It should be noted that all fast charging experiments have been conducted with the temperature compensation probe situated between the bottom of the battery and a layer of foam. It is considered that this procedure results in temperatures that are representative of field duty.

The charge current delivered to a Hawker Genesis[®] G12V13Ah10EP battery (with a resistance free voltage limit of 2.65 volts/cell) was increased between consecutive cycles until the maximum temperature within the battery (TOCell) reached about 60°C (Figure 2-5). This temperature is considered to be the maximum that such a battery should be subjected to during short to medium term operation. The maximum charge current that resulted from these experiments was 110 A (i.e., 11 C).

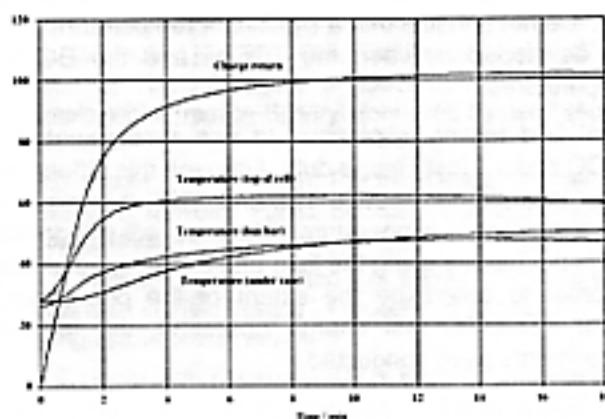


Figure 5. Temperature and Charge Return During Maximum Practical Fast Charge Studies of Hawker Genesis[®] G12V13Ah10EP

The time taken to achieve a charge return of 0% to 80% and 0% to 100% at 11C was 2.5 and 9 minutes, respectively (see Figure 3-5). The TOCell temperature reached a maximum of 62°C after 5 minutes (charge return of ~95%), then remained stable for another 8 minutes (105% charge return) before slowly decreasing. As with the absolute maximum charge rate experiments, the rate of change in BUS and BOCase temperatures were lower than in the TOCell temperature. For example, the TOCell temperature reached a maximum of 62°C after 95% charge return, whereas the BUS and BOCase temperatures were 45°C and 41°C, respectively, at the same charge level.

In summary, the maximum charging current for the Hawker Genesis[®] technology has been determined. At a charge rate of 29 C, 80% and 100% charge return can be achieved in 80 and 100 seconds, respectively. Safety and battery longevity, however, are questionable at this

charging rate. Charging at 11C is considered to be the maximum practical rate for this technology for short to medium term operation.

INVESTIGATION OF BATTERY TEMPERATURE –

Examination of temperature data presented, shows that fast charging can induce a significant temperature difference between the top and bottom of cell groups. Moreover, the extent of the temperature differential appears to be dependent upon the magnitude of the charge current. For example, after 100% charge return, the differences between the top of cell group (TOCell) and bottom of case (BOCase) temperatures at 11C and 29C charge rates were about 15°C and 32°C, respectively.

It has been previously established that the vast majority of heating occurring during fast charging is due to resistive effects, i.e., I^2R losses [12]. Also, preliminary mathematical modeling has demonstrated that the current density throughout battery plates during fast charging can be considerably higher at the top of the grids than at the bottom [13]. Hence, given the high currents used in the fast charging experiments described in the prior Section, it is not unusual that a significant temperature gradient developed between the TOCell and the BOCase temperatures.

Initial field testing is planned to use a combination of PSOC and 6C fast charge duty. Although this differs from that described above (viz., 11C and 29C), it is expected that a significant temperature difference will still develop within the battery using the field test charging conditions. In order to determine the extent of the phenomenon under PSOC/6C fast charge operation, the following experiments were conducted.

The TOCell and BOCase temperatures of several batteries were monitored during repetitive PSOC (20 and 70% SOC)/6C fast charging duty. A typical temperature response is shown in Figure 6. The TOCell and BOCase temperatures increased slightly from 22°C to 23°C during the initial discharge (100% to 20% SOC, Regime 1). Both temperatures increased markedly during the following charging period, with the TOCell and BOCase temperatures reaching 35°C and 27°C, respectively. Interestingly, the TOCell temperature decreased to 30°C during the following discharge, whereas the BOCase temperature remained steady at 27°C.

Both battery temperatures increased during the second charging period, with the peak TOCell and BOCase temperatures reaching 41°C and 31°C, respectively. Battery temperatures continued to increase during cycling until after the completion of the fourth charge when the BOCase temperature reached 35°C at which time battery cycling was interrupted. After about 20 minutes at open circuit, the temperature dropped below 35°C and cycling resumed. After the sixth discharge/charge cycle the

TOCell and BOCase temperatures reached peak values of about 45°C and 37°C, respectively.

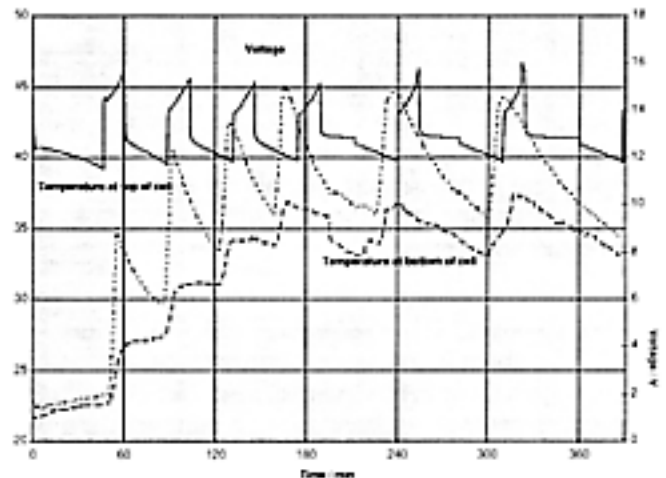


Figure 6. Temperature Within Genesis Battery During PSOC/6C Fast Charge Operation

At this stage it is useful to consider the affect of temperature on the active material utilization (AMU) of lead acid batteries. It is well known that this parameter, and therefore battery capacity, increases with increasing temperature. A general rule of thumb suggests that a rise of 10°C increases capacity by between 10 to 15%. Hence, given this relationship and the significant difference that occurs between the TOCell and BOCase temperatures during PSOC/fast charge duty, it is reasonable to expect that the hottest part of the battery will have a higher AMU than cooler locations during the following discharge. In a field situation, this may mean that EV batteries will experience preferential discharge at the top of the cell groups if vehicles are driven soon after PSOC/fast charging duty. This phenomenon is analogous to the preferential charge/discharge that occurs when significant electrolyte stratification is present in a cell. The only difference, however, is that the former occurs due to a temperature gradient rather than a variation in the relative density of the acid.

Several strategies can be employed to minimize the extent of temperature gradients that occur within batteries during PSOC/fast charging duty. The most obvious method is to decrease the charge rate. However, this unfortunately reduces the benefits of PSOC/fast charge operation. The most effective method for reducing temperature gradients induced through PSOC/fast charging duty is to optimize the plate design. For example, the current density throughout plates of an ideal battery would be not vary significantly during PSOC/fast charge cycling. This could be achieved with the following modifications; (i) smaller grids (height and width); (ii) reduced and increased lead loading at the bottom and top of grids, respectively; (iii) current take-off (i.e., tabs) at both the top and bottom of grids.

CONCLUSION

The performance of the Hawker Genesis[®] modules charging at 5C in field testing has been extremely encouraging. With 697 cycles at 5C using a 20% to 80% SOC fast charge cycle, the ALABC goal of 800 cycles appears to be achievable. Optimization of the fast charge cycle should provide further improvement of the results that allow the ALABC goal to be achieved. In addition to good cycle life, the fast charge regime has demonstrated the ability to extend vehicle range through the use of multiple charges in a single shift/day.

Charge times using the 5C algorithm met the ALABC goal for charging to 80% SOC (from 20% SOC) in 10 minutes and very nearly met the ALABC goal for charging to 50% (from 20% SOC) in 3 minutes. The charge time is easily fast enough to allow recharge during a short break period for the driver, allowing the battery to deliver 60% of capacity per charge as many times during the day as is necessary to fulfill the vehicle mission.

The maximum charging current for the Hawker Genesis[®] technology has been determined. At a charge rate of 29 C, 80% and 100% charge return can be achieved in 80 and 100 seconds, respectively. Safety and battery longevity, however, are questionable at this charge rate. Charging at 11C has been demonstrated to be the maximum practical rate for the Hawker Genesis[®] for short to medium term operation. The 11C rate allows charge times (80% charge return) as short as 2.5 minutes, well within the ALABC goal.

At high charge rates, significant temperature gradients from top to bottom of the plates have been measured. This gradient can effect the utilization of active material across the length of the plate. The temperature gradients also impact temperature compensation schemes for chargers. As the charger typically measures only a single temperature for the battery pack, it can at best represent the "average" temperature of the battery pack. In conditions where significant temperature gradients exist, the hottest regions of the battery will, therefore, be overcharged and the cooler regions of the battery will be undercharged.

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