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Rapid partial charging of lead/acid batteries

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Abstract

Rapid partial-charge cycling tests, in which the battery received only 5 or 15 min of high-current charge in each cycle, were carried out for a number of commercial lead/acid batteries. It was found that valve-regulated batteries retained their capacity well, and their full discharge capacity was usually recovered in an extended recharge following five to ten rapid partial-charge cycles. Flooded batteries, tested under stationary conditions, did not perform as well as the valve-regulated batteries, which may have been caused by electrolyte stratification. The experimental data indicated that rapid charging was beneficial to the cycle life of a battery. Heat analysis indicated that the ohmic heat was the major contributor to the total heat generated in the rapid partial-charging process.

Keywords: Lead/acid batteries; Charge; Electrolytes; Heating

1. Introduction

Lead/acid battery technology is essentially ready for electric vehicle (EV) applications, which are urgently needed to avoid the detrimental environmental effects of internal combustion vehicles. Although statistics show that the vast majority of people travel less than 60 miles per day, the range of 60 miles per charge is perceived as an obstacle to consumers' acceptance of EVs powered by lead/acid batteries. One way to solve this problem is to rapidly charge EVs to extend the travel range. This possibility was, however, rejected previously. A widely accepted concept was the ampere-hour law, pronounced by Woodbridge in 1935 [1]: "As a result of numerous tests, it has been found that if the charging rate in amperes (A) is kept below a value equal to the number of ampere-hours (Ah's) then out of the battery the conditions as to gassing and temperature will be met". According to this law, explained Vinal [2], "in 1/2 hour the most that can be given the battery is about 50 per cent of a full charge; the excess input is wasted in gassing".

Since 1991, Valeriote and co-workers have demonstrated [3–7], however, that lead/acid batteries can be rapidly recharged with neither apparent detrimental effects on the batteries, nor excessive waste of charging energy. If rapid partial recharges can be applied repeatedly without damaging the battery, then the daily travel range of a vehicle powered by lead/acid batteries can be extended for long distance trips.

2. Experimental

MinitChargers™ Model MC36-300A manufactured by Norvik Technologies, Mississauga, Ont., Canada, which charged batteries with a constant resistance-free voltage, V_{rf} [5,8–11], were employed in this investigation. The chargers interrupted the charging current, many times per second, measured the resistance-free battery voltage, and then adjusted the applied voltage to maintain a set value of the resistance-free voltage. The applied charging voltage was also adjusted to compensate for measured temperatures on the sidewall of the battery which deviated from 25 °C.

Thirty lead/acid batteries of various types: flooded and valve-regulated, gelled electrolyte and absorptive glass mat configurations, with grids made of pure lead and various alloys, using flat plates, tubular positives and cylindrically wound constructions were rapid-charge tested. Most of them were commercial batteries, while the rest were prototypes made by battery manufacturers. The test batteries were repeatedly subjected to between three and twenty consecutive rapid partial-charge cycles, in which the batteries were charged for 5 or 15 min at a high current and then discharged at either the 2 or 3 h rate to a depth-of-discharge (DOD) of 80%. The voltage, current, internal pressure, as well as the internal and external temperatures of the test batteries were continuously monitored and recorded during the test.

A rapid charge referred to in this paper is defined as follows:

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Recharge time (min)	Charge returned (80% DOD) (%)
5	50
15	80
240	100

3. Results and discussion

Although, as mentioned previously, thirty batteries were tested in this investigation, we can only present selected results in this paper.

3.1. Prismatic valve-regulated lead/acid batteries with absorptive glass mat separators

Five models of this type of battery from various manufacturers were tested in rapid-charge cycling. Some of the results for two batteries in this group are discussed below.

Battery A was a 20 kg, 12 V battery with a measured internal resistance of 3.3 mΩ when fully charged. It was a prototype battery designed for deep-discharge cycling. The initial capacity of the battery was 48 Ah. It went through 209 cycles, including partial and full rapid recharges, and delivered a cumulative output of 6780 Ah. At the end of the test, its discharge capacity was 106% of the initial value. Fig. 1 shows the Ah inputs and outputs in two consecutive sets of ten 15 min charge cycles, cycles 126 to 135 and cycles 139 to 148. In these cycles, the battery was charged with a resistance-free voltage (V_{rf}) of 14.1 V and a current limit of 250 A, and discharged at the 2 h rate to 80% DOD, except in the tenth cycle of the set: in cycles 135 and 148, the battery was discharged to 100%, with a cut-off voltage of 11.55 V, DOD. In cycles 125, 136 to 138, 149, and 150, the battery was charged for 4–5 h to attain a fully charged state, and discharged to 100% DOD, except for cycles 125 and 138, when the battery was discharged to 80% DOD. The figure indicates that the Ah output decreased with partial-charge cycling, and most of the reduction occurred in the first few cycles. The battery, when discharged to 80% DOD, delivered 50, 45, and 42% of the full capacity, after the third, the fifth, and the tenth 15 min charges, respectively, which corresponded roughly to states-of-charge (SOCs) of 70, 65, and 62%, respectively, before each discharge. The figure also shows that, after ten partial-charge cycles, a single extended recharge recovered all the lost capacity. Rapid charging caused elevated temperature in the battery, as shown in the figure. The maximum internal temperature during rapid recharge increased quickly in the first three cycles to about 60 °C. Further partial-recharge cycles did not increase this temperature. The actual maximum temperature rise was 23 to 26 °C in the first cycle of a test set, and decreased to about 18 °C in the sixth cycle with the decreased charge acceptance.

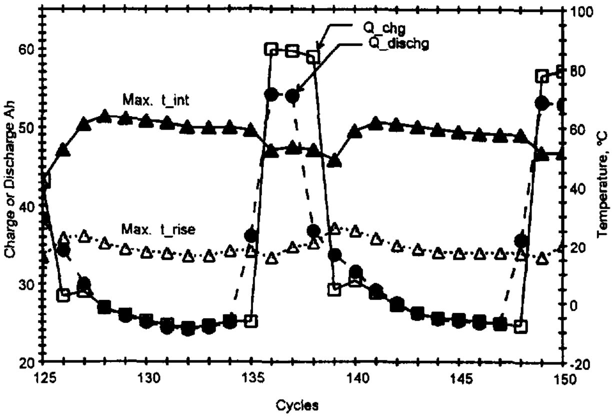

Fig. 1. Input and output Ah's and temperatures of Battery A, a prismatic VRLA battery with absorptive glass mat, in rapid 15 min charge cycles with a current limit of 250 A.

An analysis of the heat generation during the 15 min charge periods is given in Fig. 2. The first to the tenth cycles in the figure correspond to the 139th to the 148th cycles shown in Fig. 1. The calculation of total, ohmic and non-ohmic heating rates was discussed in a previous paper [5]. In the following discussion, the definitions of ohmic and non-ohmic heating rate are defined as:

(i) ohmic heating rate =

$$I^2R \tag{1}$$

where I is the charging current, and R the internal resistance of the battery, and

(ii) non-ohmic heating rate =

$$I(V-V_0)-I^2R \tag{2}$$

where V is the charging voltage applied, and V_0 the open-circuit voltage of the battery.

At the very beginning of the charging, in the first cycle, ohmic heating consumed 10% of the total power input to the battery. It decreased almost linearly with the decreasing battery resistance for the first 3 minutes of charging at the 250 A limit, and then decreased at a higher rate with the decreasing current. The non-ohmic heating rate was small at the very beginning, but increased quickly with charging, peaking at the end of the 3rd min of charge. At that point, it consumed 8% of the total power input. After 5 min of charging, the non-ohmic heating became the major contributor to the total heating. A calculation indicated that, in the first 4 min of charging, a substantial amount (14%) of power input was dissipated in heat generation. The contributions from the ohmic and the non-ohmic sources to the total heat generation, in this first 15 min charge cycle, were about equal. At the beginning of the 15 min charge in the next cycle, the SOC of the battery was lower than that in the previous cycle. As a consequence, the heat generated from the non-ohmic sources became smaller, and that from the ohmic source became larger. After four consecutive 15 min charge cycles, the charge acceptance stabilized and stayed at the same level with further short-charge cycling. Meanwhile, the ratio of ohmic heat and non-ohmic heat also became constant, with the ohmic dominating.

Battery B, weighed 17.5 kg, was also a 50 Ah, 12 V battery with an internal resistance of 3.5 mΩ. The capacity of the

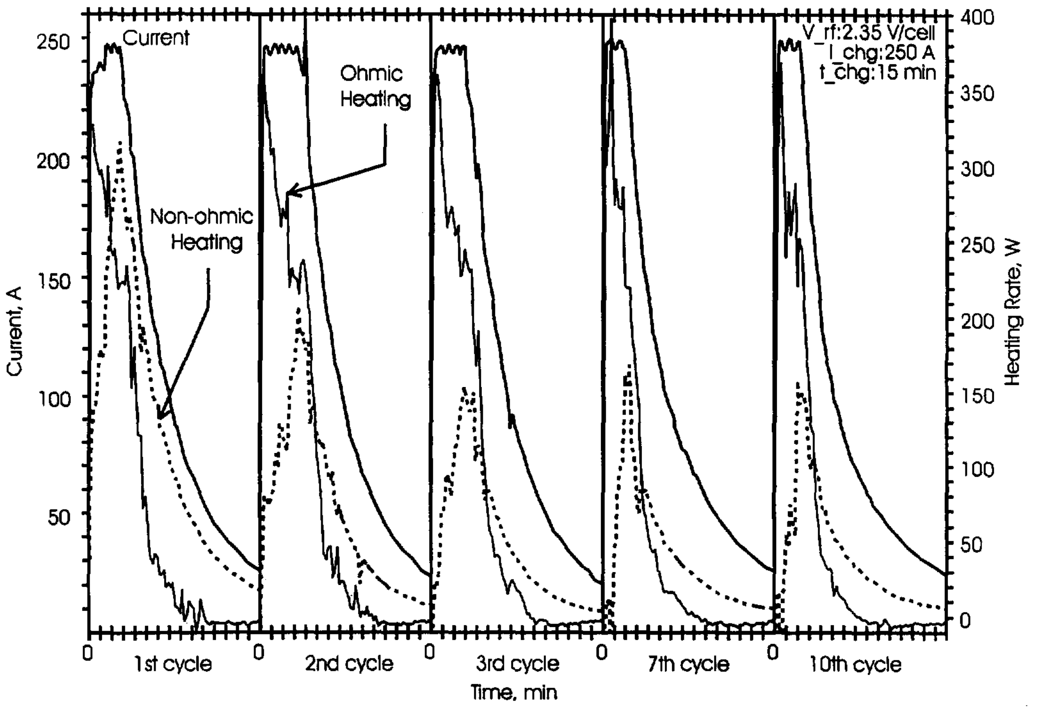

Fig. 2. Ohmic and non-ohmic heating rates and currents in ten consecutive 15 min rapid partial recharges for Battery A, a prismatic VRLA with absorptive glass mat.

battery was 51 Ah at the initial stage of the cycling test. It was a prototype EV battery. The battery was tested for 106 rapid-charge cycles; the accumulated output was 3612 Ah. The capacity in the last test cycle was 87% of the initial value. Following a full charge and 100% DOD discharge, three consecutive 5 min rapid-charge test sets, starting from cycle 66, are presented in Fig. 3. There were five 5 min charge cycles in each test set. In each rapid partial-charge cycle, the battery was charged for 5 min at a V_{rf} of 14.4 V with a current limit of 250 A, and discharged at the 3 h rate to 11.6 V (80% DOD). In each set, after five partial-charge cycles, the battery was charged for 5 h, and then discharged to 80% DOD. The exception was the last set, in which the battery was discharged to 100% DOD in the 5th cycle (cycle 83), followed by a cycle in which the battery was fully charged and discharged. The experimental data indicated that, after three 5 min charge cycles, the battery lost very little capacity with further partial-charge cycling. The 100% discharge in cycle 83 determined that the 5th short recharge had brought the SOC of the battery to 60%. The figure also shows that a single long recharge, after five consecutive partial-recharge cycles, recovered all the lost capacity. The internal temperature of the battery rose with the cycling to about 52 °C. The maximum temperature rise in each partial-charge cycle was 17 °C.

A heat analysis is presented in Fig. 4, where the ohmic and non-ohmic heating rates in five 5 min recharges, cycles 67 to 71, are plotted. In the first cycle, after the 250 A current was applied, the total input to the battery was 3.8 kW. At the beginning, about 8% of that input power was dissipated as ohmic heat. As the charging proceeded, the ohmic heating decreased with decreasing resistance, and the non-ohmic heating increased with the increasing SOC. The total heating

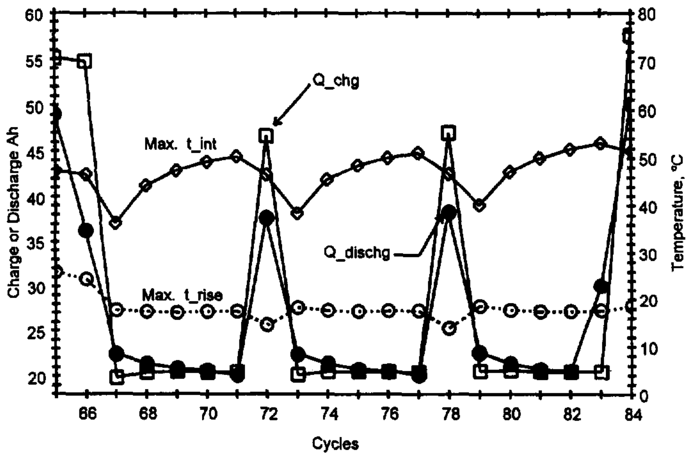

Fig. 3. Input and output Ah's and temperatures of Battery B, a prismatic VRLA battery with absorptive glass mat, in rapid 5 min partial-charge cycles.

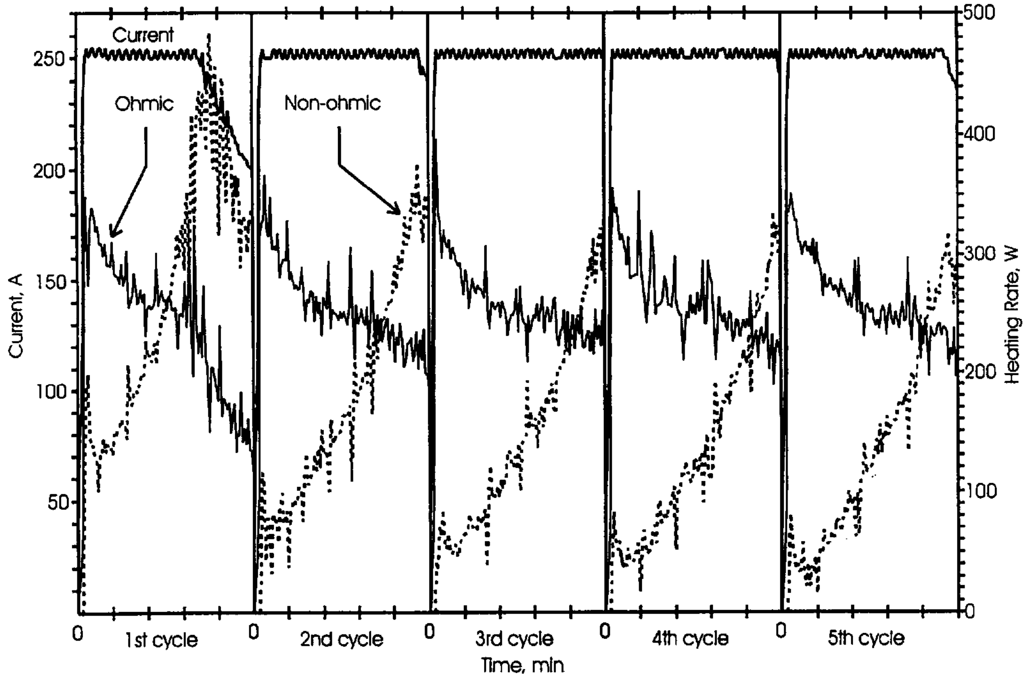

Fig. 4. Ohmic and non-ohmic heating rates for Battery B, a prismatic VRLA battery with absorptive glass mat, in five consecutive 5 min rapid partial-charge cycles, with a V_{rf} of 2.40 V/cell and a current limit of 250 A.

rate peaked when the battery had been charged for 3.5 min, consuming 17% of the total input. After that, the non-ohmic heating became the major component. With further cycling, the ohmic heating characteristic stayed almost the same, but non-ohmic heating decreased with decreasing SOC. Thus, at the 5th cycle, the total heat (integrated power) from the non-ohmic sources was only about a half of that from the ohmic source. Even with the reduced non-ohmic heating, about 10% of the total energy input, compared with 14% in the first cycle, was dissipated as heat.

3.2. Cylindrical VRLA batteries with absorptive glass mat

Many units of a spirally-wound 12 V cylindrical battery have been tested. This battery, weighing 20.4 kg with a 50 Ah capacity, was designed for deep-discharge cycling and has been tested in EVs. Before cycling, this battery had a internal resistance ranging from 2.4 to 2.6 mΩ. The spirally wound electrode assemblies were tightly packed against the battery case. The wall of the case was contoured about the cylindrical cell assemblies, and, therefore, had a larger surface area than that of an equivalent prismatic case. The configuration provided the battery with a better heat dissipation capability.

One of the batteries, Battery C1, was subjected to an extended rapid partial-charge cycling test. In each cycle, the battery was given a 15 min rapid charge with a current limit of 250 A, and then discharged at the 2 h rate to 11.6 V (80% DOD). Every 5 rapid partial-recharge cycles was followed by an extended recharge of 4 h with a current limit of 100 A. After every 50 cycles, the battery was discharged to 100% DOD, and then fully charged for three cycles. This is depicted in Fig. 5, where the input and output Ah for 50 test cycles are given. As seen for Battery A, as shown in Fig. 1, its discharge capacity stabilized after four short-charge cycles. In the 50 cycles between the two sets of three full charge/discharge cycles, the discharge capacity decreased slightly with cycling. At the end of this 50 cycle set, the battery was discharged to 100% DOD in cycle 251. The output of this discharge was 38 Ah. If the full capacity is assumed to be 52 Ah, this indicates that the SOC of the battery was 73%, before the discharge. Usually, it took about three full charge/discharge cycles to bring the capacity to the maximum value. One of the test batteries, at the time when this paper was written, had completed 866 cycles, as shown in Fig. 6, and accumulated 29 929 Ah of output. The figure shows that, at cycle 854, the battery still had a capacity of 49 Ah.

For comparison, three batteries of the same kind were given a conventional charge cycling test. In each cycle, they were charged for 10 h with a current limit of 10 A, and discharged at the 2 h rate to 11.6 V (80% DOD). About every 50 cycles, the test batteries were discharged to 10.5 V (100% DOD) and then fully charged for three cycles. These batteries failed (discharge capacity falling to 40 Ah) after about 250 cycles, with an average accumulated output of 10 000 Ah each. Fig. 7 shows the input and the output charges of one of the batteries, Battery C2, during the cycle-life test.

One obvious difference between the two kinds of test was the ratio of charge Ah to discharge Ah. In the conventional charge cycling test, the batteries were overcharged in every cycle, and, in the rapid partial-charge cycling test, the batteries were only overcharged once every 6 cycles. The averaged overcharges accepted by the three batteries in the conventional charge cycle test mentioned previously were 125, 116,

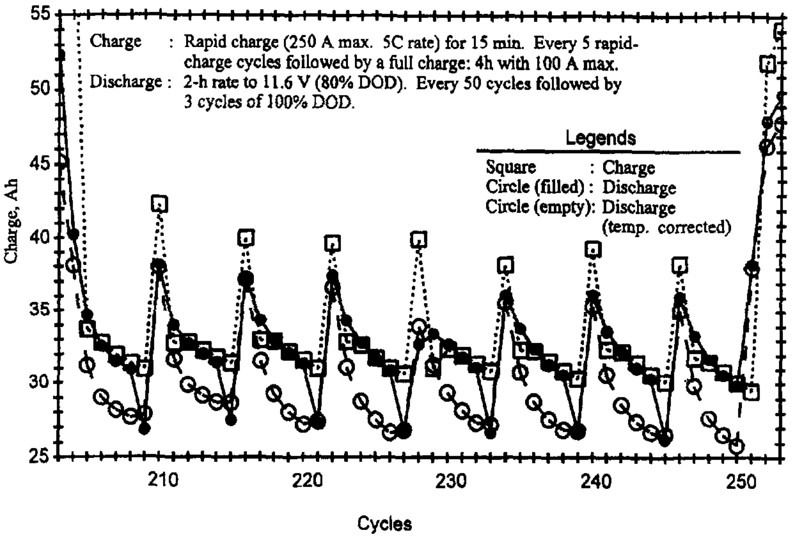

Fig. 5. Input and output Ah's for Battery C1, a cylindrical VRLA battery with absorptive glass mat, for cycles 202 to 252, in which the battery was charged at a V_{rf} of 2.38 V/cell with a current limit of 250 A for 15 min each cycle. After every 5 partial-charge cycles, the battery was charged for 4 h at a V_{rf} of 2.38 V/cell with a current limit of 100 A.

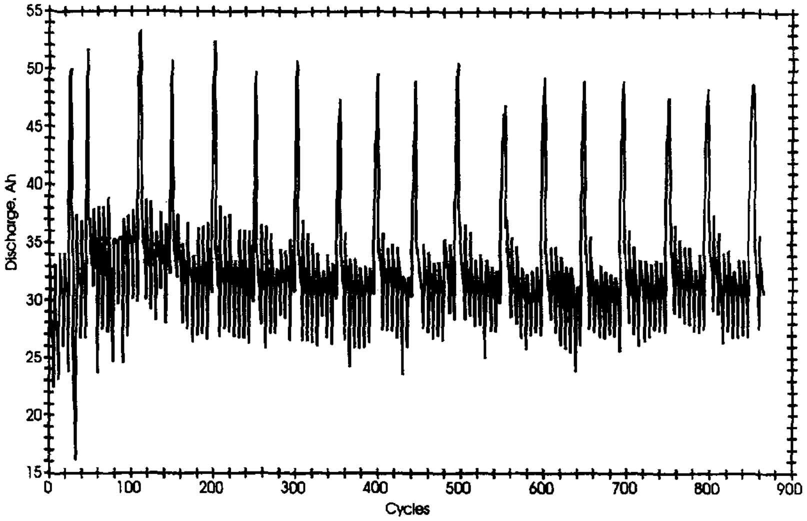

Fig. 6. Discharge output in a rapid 15 min partial-charge cycle test for Battery C1.

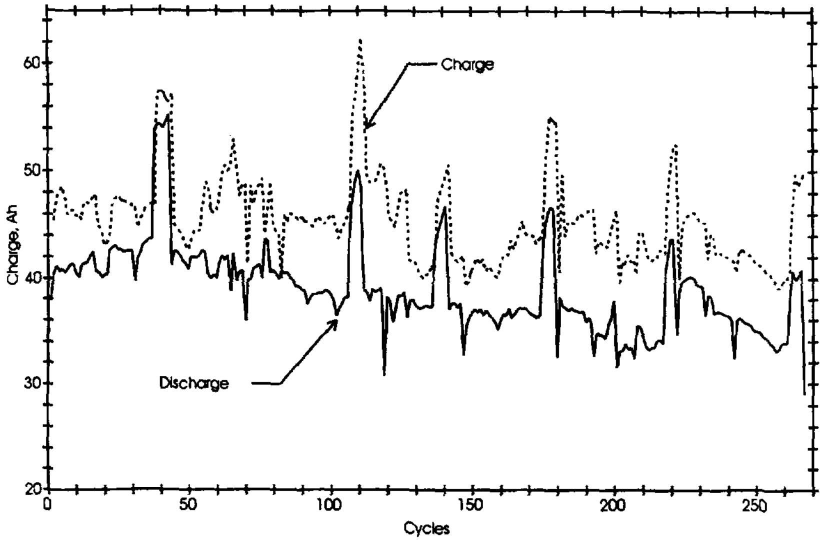

Fig. 7. Input and output Ah's for Battery C2 in a conventional charge cycle test.

and 112%, respectively, and the correspondent cycle lives for these batteries were 237, 250, and 252. The tear-down analysis performed on these failed batteries showed that grid corrosion was not the cause of failure. The average overcharge received by Battery C1 during its 886 rapid partial-charge cycles was 104%. A high overcharge might be detrimental to a VRLA battery, but it is unlikely that the lowering of the overcharge from 112 to 104% was the sole cause for the extension of the cycle life by a factor larger than three.

3.3. Prismatic VRLA batteries with gelled electrolyte

Battery D was a 29.5 kg commercial 12 V deep-discharge battery with a 65 Ah capacity at the 3 h rate. It had a relatively high internal resistance: 4.7 mΩ, charged; 7.5 mΩ, 80% discharge, and 11.7 mΩ, fully discharged. It went through 183 various rapid-charge test cycles, and retained 85% of the initial capacity.

It was found that with a charging V_{rf} set at 14.4 V and a current limit at 200 A, the 15 min 80% return demand could be met. After four rapid partial-charge cycles, the battery could still deliver 60% of the total initial capacity. When the current limit was raised to 300 A, which was the current limit of the charger employed in this investigation, 47% of the previous discharge was returned to the battery in 5 min.

A heat-generation analysis of the 15 min charges in three consecutive partial-charge cycles is shown in Fig. 8, where several noteworthy features can be observed. In comparison with those batteries discussed previously, a higher initial charge voltage was automatically applied by the charger to compensate for the higher resistance of the battery and maintain the resistance-free voltage constant. The corresponding ohmic heating was high, consuming 11% of the total wattage input. This high initial charging voltage appeared to also cause a high non-ohmic heating. In the 1st min of charging during the first partial-charge cycle, cycle 47, the non-ohmic polarization increased with time, resulting in rising non-ohmic heating. To counter this rising non-ohmic overpotential, the applied charging voltage was increased. Near the end of the 1st min, the total heat generation consumed about 18% of the total charging power. After that, with the declining ohmic resistance, the charging voltage was reduced, which in turn appeared to cause the non-ohmic polarization to decrease. This decline of non-ohmic heating rate was, however, reversed after the 3rd min of charging, because of the increased SOC. In the first 7 min of charging, about 16% of the input power was dissipated as heat. In the first cycle, cycle 47, the magnitudes of the heats generated from the ohmic and the non-ohmic sources were comparable. In the following two cycles, as shown in Fig. 8, the non-ohmic heating became smaller with the lowered SOC, and the heat from the non-ohmic source in the 3rd cycle was only about a half of that from the ohmic source.

When the current was raised to 300 A to meet the 5 min 50% return demand, the total heating rate was about 800 to 900 W, close to 20% of the total charging energy input.

The peaking and decline of the non-ohmic heating in the first 3 min of rapid charging are difficult to understand in terms of electrochemistry, because the charging current during this period was kept constant. It was also observed that, in the same time period, the internal gas pressure rose quickly after the charging voltage was applied, peaked within 2 min, followed by a decline or plateau and then a rise, showing exactly the same trend as that of the non-ohmic heating. It seemed to suggest that the electrolysis of water was associated with the variation of the non-ohmic polarization. In the previous discussion, in the calculation of the total heating rate, as given in Eq. (2), the electrolysis of water was not considered. In reality, a high non-ohmic polarization of the elec-

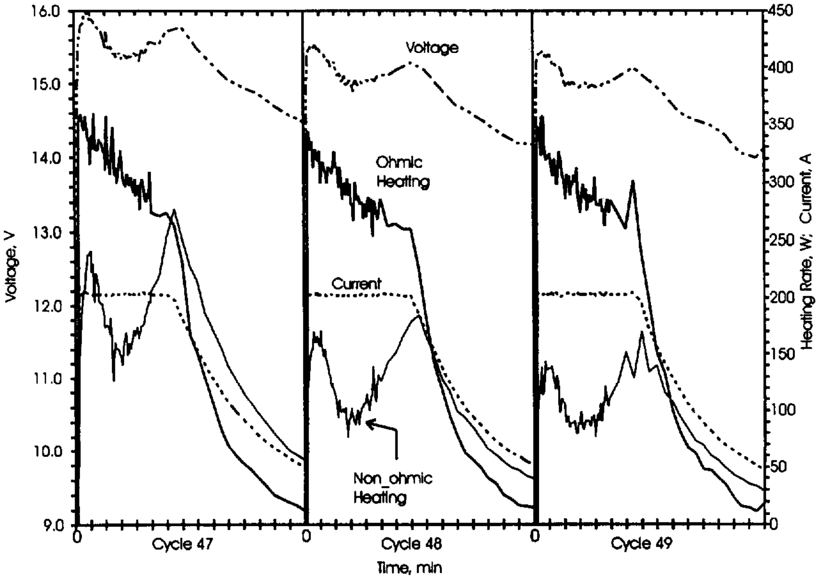

Fig. 8. Charging voltage, current and ohmic and non-ohmic heating rates for Battery D, a prismatic VRLA battery with gelled electrolyte, in three consecutive rapid 15 min charge cycles.

trodes encouraged the parasitic reactions, which all resulted in more heat being generated in the gas-recombination environment.

3.4. *Flooded electrolyte batteries*

Several prismatic flooded electrolyte 12 V batteries were tested. One of them, Battery E, was a 52 Ah battery, with positive grids containing 4.7% Sb and negative grids containing 0.1% Ca and 0.35% Sn. The internal resistance of the battery was 6.4 mΩ when charged. It had gone through 173 rapid-charge cycles, when its capacity fell to the 81% level of the initial value. Three consecutive sets of 15 min rapid partial-charge cycles for this battery are presented in Fig. 9. Each set contained ten partial-charge cycles. In each cycle, the battery was charged with a V_{rf} of 14.4 V and a current limit of 300 A for 15 min, and then discharged to 11.54 V (80% DOD) at the 3 h rate. One exception was cycle 132, the last cycle in the last set, in which the battery was discharged to 100% DOD. At the end of each cycling set, the battery was given an extended charge and the electrolyte was thoroughly stirred with air bubbles. Fig. 9 shows that the battery, in contrast to the VRLA batteries discussed previously, lost capacity continuously during the ten cycles of partial-charge cycling. In addition, the total capacity loss for the flooded battery was larger. The figure shows that, after ten 15 min charge cycles, the battery lost about 65% of its capacity. The battery also went through many 5 min partial-charge cycles. It was found that it lost 70 to 75% of its capacity in ten such cycles. However, as shown by Fig. 9, after each set of cycles, an extended charge cycle and a thorough stirring of the electrolyte recovered all the lost capacity.

A heat analysis for consecutive 15 min charges is presented in Fig. 10. As the charge acceptance decreased with the partial-charge cycling, the heats generated from the ohmic and non-ohmic sources decreased also. The ratio of these two heats remained, however, essentially unchanged, unlike those for the batteries discussed before.

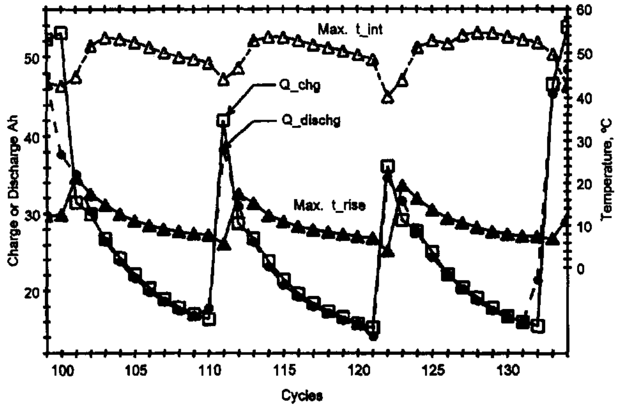

Fig. 9. Input and output Ah's and temperatures in rapid 15 min charge cycles for Battery E, a prismatic flooded battery.

All evidence indicated that the larger loss of capacity and the unchanged ratio of the heats from the ohmic and non-ohmic sources in partial-charge cycling were caused by stratification of the free electrolyte in the battery tested in the stationary condition. This unfavourable consequence is likely of less concern for an EV battery, the movement of which may sufficiently agitate the electrolyte to prevent stratification.

4. Conclusions

1. Numerous lead/acid batteries, varying quite widely from each other in size, construction, grid alloy, and other aspects, have been subjected to rapid partial-charge cycle tests. It was found that all the test batteries accepted rapid charge well, and the 5 min 50% return and 15 min 80% return criteria could be met with appropriate charging conditions.

2. In meeting the 5 min 50% return and 15 min 80% return criteria, when the total charging time was limited to 15 min

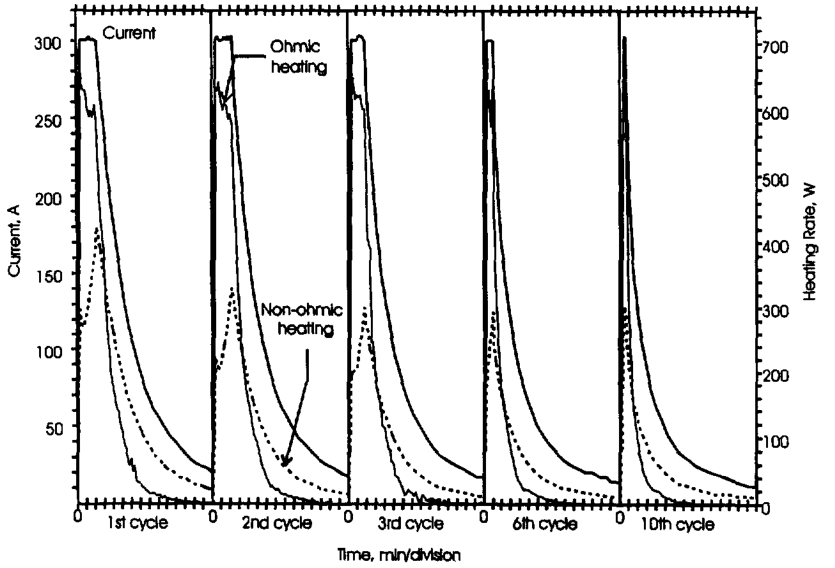

Fig. 10. Ohmic and non-ohmic heating rates in rapid 15 min charge cycles for Battery E.

or less, the temperature rise as the result of the rapid charge, in general, was less than 25 °C.

3. In continuous partial-charge cycling, the charge acceptance and the discharge capacity decline with cycling. For VRLA batteries, the loss occurred mainly in the first 3 or 4 partial-charge cycles; very little additional loss occurred with further partial-charge cycling. For flooded batteries, tested in a stationary condition, the loss was larger than that for VRLA batteries, due to stratification of the electrolyte, and it increased continuously with cycling. For all batteries, most of the loss could be recovered with a single extended recharge. However, for flooded batteries, a vigorous agitation of the electrolyte was also needed.

4. No ill effects of rapid charge on either capacity or cycle life have been observed. On the contrary, the rapid partial-charges have extended the cycle life of Battery C, a cylindrical VRLA battery with absorptive glass mat, by at least three times in terms of total ampere-output of the battery. At the time of writing this paper, this battery had gone through 866 cycles, accumulated a total output of 29 929 Ah, and had retained its capacity intact. Three batteries of the same kind, cycled with a conventional charging regime, each failed after about 250 cycles, with an accumulated total output of 10 000 Ah.

5. When a battery with a high internal resistance was subjected to rapid charging with a constant resistance-free voltage, a high charging voltage had to be applied to compensate for the high voltage drop (IR). To avoid excessive heating, it is advisable that a battery to be used in rapid charge applications be constructed to have an internal resistance of 2.5 mΩ or less.

6. A battery with gelled electrolyte with a relatively high internal resistance of 4.7 mΩ showed a relatively high non-ohmic heating rate in the initial stage of rapid-charging, which might be associated with the electrolysis of water.

7. When a battery was repeatedly subjected to rapid partial-recharges the ohmic heat contribution became more important than that from non-ohmic sources.

Acknowledgements

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References

[1] J.L. Woodbridge, *Trans. Am. Inst. Elec. Eng., 54* (1935) 516.
[2] G.W. Vinal, *Storage Batteries*, Wiley, New York, 4th edn., 1955, p. 244.
[3] E.M. Valeriote, J.K. Nor and V.A. Ettel, *Proc. 5th Internat. Lead/Acid Battery Seminar, Int. Lead Zinc Research Organization, Research Triangle Park, NC, 1991*, p. 93.
[4] E.M. Valeriote and D.M. Jochim, *J. Power Sources, 40* (1992) 93.
[5] T.G. Chang, E.M. Valeriote and D.M. Jochim, *Proc. 26th Int. Symp. Automotive Technology, Aachen, Germany, 13–17 Sept. 1993*, pp. 405–413.
[6] T.G. Chang, E.M. Valeriote and D.M. Jochim, *J. Power Sources, 48* (1994) 163.
[7] E.M. Valeriote, T.G. Chang and D.M. Jochim, *Fast Charging of Lead–Acid Batteries, 9th Annual Battery Conf. Applications and Advances, California State University, Long Beach, CA, USA, 11 Jan. 1994.*
[8] J.K. Nor, *Eur. Patent No. 0 311 460 A2* (10 Oct. 1988); *US Patent No. 5 202 617* (13 Apr. 1993).
[9] J.K. Nor, *Proc. 25th Int. Symp. Automotive Technology, Florence, Italy, 1–5 June 1991.*
[10] J.K. Nor, *Proc. 11th Int. Electric Vehicle Symp., Florence, Italy, 27–30 Sept. 1992*, Paper No. 9.03.
[11] J.K. Nor, *Proc. 26th Int. Symp. Automotive Technology, Aachen, Germany, 13–17 Sept. 1993*, Paper No. 93EL020, p. 375.