Collaborative investigation on charging electic-vehicle battery systems for night-time load levelling by Japanese electric power companies

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Abstract

In 1995, ten Japanese electric power companies and CRIEPI started a three-year collaborative investigation of battery systems for electric vehicles (EVs). In the first year, the charging procedure for valve-regulated lead/acid (VRLA) batteries connected in series in EVs has been evaluated for both night-time load levelling and prolonging the cycle life. An EV battery system with VRLA batteries can be charged by both constant current and constant current (CC–CC) and constant current and constant voltage (CC–CV) in less than 8 h under night-time conditions. The charging method with CC–CC prolongs the cycle life further than that with CC–CV. Excess charging capacity on the part of CV in CC–CV charging degrades the positive electrode through softening of the active material. A higher rate of the first current in CC–CC charging prolongs the cycle life by suppressing the softening of the positive electrode due to active-material particle growth. On the other hand, control of the uniform environment in battery boxes during the charging with CC–CC and CC–CV is very important in order to prolong the cycle life. This is because cooled batteries tend to have insufficient charge capacity due to their greater energy consumption for the electrolysis of water than uncooled ones. © 1997 Elsevier Science S.A.

Keywords: Electric vehicles; Valve-regulated lead/acid batteries; Lead/acid batteries; Charging methods; Charging current; Particle growth

1. Introduction

The popularization of electric vehicles (EVs) is expected as a result of efforts to alleviate problems related to the global environment and for the efficient utilization of energy. One of the main topics of concern for electric power supply management is how to increase night-time electric loads in order to utilize electric power generation equipment with high efficiency. In Japan, the increase in demand for air conditioning creates a load peak in the summer. In the course of a single 24 h period in summer, the ratio between the peak load, in the middle of the day, and the minimum, late at night, is close to 40%. The annual load factor is declining and currently starts at less than 60%. This low load factor diminishes the capacity utilization factor of power stations. Thus, load levelling is extremely important in order to increase the effective use and generation efficiency of power stations. The popularization of EVs will warrant the increase of night-time electric load since EV batteries can be charged with available procedures during the night. The procedures should provide complete charging in less than 8 h, and effectively increase the electric load in the minimum period between 2 and 5 a.m.

Therefore, it is necessary to investigate a new charging pattern to complete the charging of the EV battery system in a shorter time and with few steps.

Electric power companies have been undertaking the development and research of EV infrastructure and power supply management, for example, the development of new EVs [1]; a study for setting up charging stations in the near future [2]; impact of EV charging on power supply systems [3]; and performance evaluation of EVs [4]. The electric power load during the night-time can be increased for only a few hours by CC–CV charging of EV batteries which need a charging time longer than 8 h. Therefore, charging methods with a shorter time and several patterns should contribute to load levelling during the night-time [3].

Some vehicle manufacturers are proposing to produce and sell EVs with a new type of battery, e.g. a nickel/metal-hydride (Ni/MH) battery or lithium-ion battery, in a few years. Battery types for EVs should be selected according to the purpose of each field of use with respect to such factors as battery cost and performance in terms of specific energy, specific power, and cycle life. The lead/acid battery may become popular in the near-term, due to its benefits of cost, performance and easy maintenance.

Ten Japanese electric power companies and CRIEPI have started a three-year collaborative investigation of battery systems for EVs for the purpose of: (i) studying the charging of VRLA batteries for night-time load levelling; (ii) prolonging the cycle life of EV batteries; (iii) increasing the accuracy of the state-of-charge (SOC) indicator to monitor the amount of energy remaining in the batteries.

In this study, we estimate the feasibility of the charging procedure for night-time load levelling, and investigate the influence of the charging procedure on the cycle life of EV batteries connected in series.

2. Experimental

2.1. EV battery systems

Six battery systems were constructed using twelve VRLA batteries (12 V/60 Ah, type-A standardized by JEVS) in series connection. Three types of prototype batteries under development (samples A, B and C), were donated by three battery manufacturing companies in Japan.

The two battery systems with sample B were set in battery boxes with fans (Fig. 1), which simulated the battery arrangement under the floor of EVs. The other four systems with samples A and C were arranged on the floor of the laboratory room under a constant ambient temperature of 25 °C, with more than 10 cm between each battery to suppress the effects of battery heating on neighbours in the same system.

2.2. Discharge and charge patterns for life test

The discharge and charge of battery systems were tested in life tests. The discharge pattern was the US Simplified Federal Urban Driving Schedule (SFUDS) [5] under the
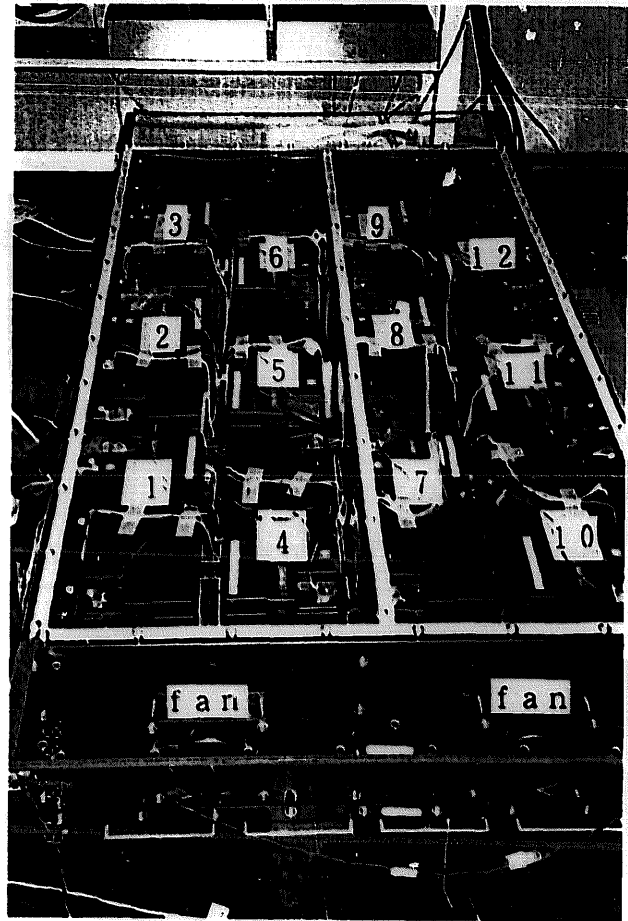

Fig. 1. Battery box with fans.

conditions of capacity of 48 Ah or voltage of 84 V. Two types of discharge for measurement of discharge capacity were assessed every 50 cycles. One was discharge with a constant current of $1/3C$ (20 A) under 118.8 V (9.9 V/module), and the other was SFUDS discharge to less than 84 V. In these measurements, the systems were charged by constant current and constant current (CC–CC) methods with a first constant current of $1/5C$ (12 A) or $1/4C$ (15 A) to a predetermined voltage and a second constant current of $1/20C$ (3 A) at the capacity corresponding to the preceding discharge capacity (Table 1).

The charging conditions were set so as to achieve complete charging of the battery systems in less than 8 h under night-time conditions, as summarized in Table 1. The four systems with samples A and B were tested in order to compare the effects of the charging methods on cycle life. One of the two samples was charged with CC–CC and the other with CC–CV. The systems with sample B were arranged in battery boxes. The two systems with sample C were charged under CC–CC with the first currents of $1/5C$ and $1/2C$, in order to compare the effects of the magnitude of the first current.

2.3. Definition of cycle life

In this study, the cycle life of the systems is governed by three parameters including battery voltage, discharge capac-

Table 1
Charging condtions

| Sample	Cycle test	Measurement for discharge capacity
A-1	CC–CV: CC = 0.4.C and CV = 176.4 V controlled capacity: 120% preceding discharge capacity	CC–CC: 1st CC = 0.2C (until 172.8 V) 2nd CC = 0.05C (for 4 h)
A-2	CC–CC: 1st CC = 0.2C (until 172.8 V) 2nd = 0.05C (for 4 h) controlled capacity: 130% preceding discharge capacity	same as A-1
B-1	CC–CV: CC = 0.25C and CV = 180.0 V controlled capacity: 115% preceding discharge capacity	CC–CC: 1st CC = 0.25C (until 172.8 V) 2nd CC = 0.05C regulated capacity: 115% preceding discharge capacity
B-2	CC–CC: 1st CC = 0.2C (until 172.8 V) 2nd CC = 0.05C (for 4 h) controlled capacity: 115% preceding discharge capacity	same as B-1
C-1	CC–CC: 1st CC = 0.2C (until 174.0 V) 2nd CC = 0.05C controlled capacity: 115% preceding capacity	CC–CC: 1st CC = 0.2C (until 174.0 V) 2nd CC = 0.5C regulated capacity: 125% previous discharge capacity
C-2	CC–CC: 1st CC = 0.5C (until 174.0 V) 2nd CC = 0.05C controlled capacity: 115% preceding capacity	same as C-1
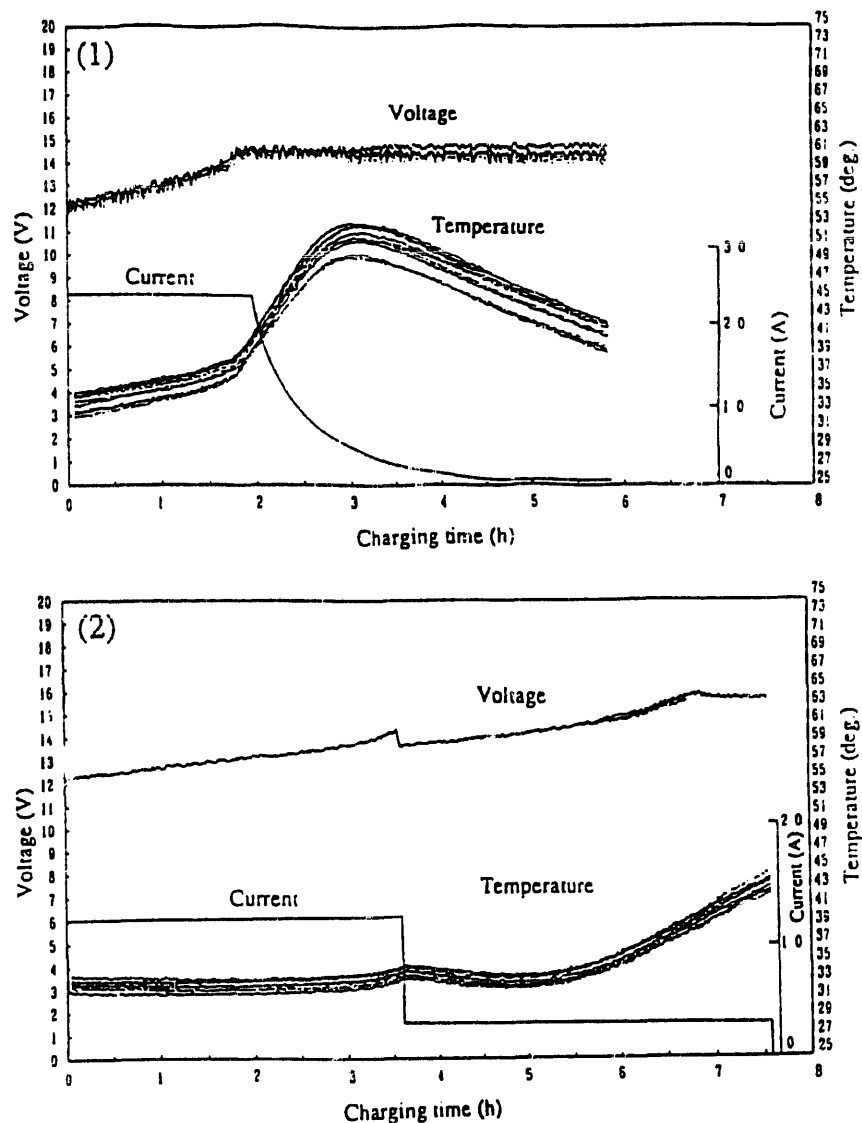
Fig. 2. Charging profiles of the battery system with sample A at the 100th cycle: (1) CC–CV. and (2) CC–CC.

ity with the SFUDS pattern and constant current. The cycle life test was stopped when any battery in the system showed a voltage decrease to zero upon discharge during the cycle test, a decrease of the discharge capacity measured from the SFUDS pattern every 50 cycles to less than 80% of the first discharge capacity, or a decrease of the discharge capacity obtained with a constant current to less than 48 Ah.

After finishing the cycle life test, the discharge capacity of every battery in the system was measured with constant current down to 9.9 V. Some batteries were opened and analysed by X-ray diffraction (XRD), scanning electron microscopy (SEM), electron probe microanalysis (EPMA), porosimetry or chemical analysis in order to elucidate the mechanism of degradation of the batteries under charge conditions.

3. Results and discussion

3.1. Charging time

All six battery systems were charged within 8 h for night-time conditions under the above specifications (see Figs. 1, 5 and 8). This indicated that the electric power consumption due to charging EV battery systems creates a significant demand that warrants the increase of night-time electric load.

3.2. Comparison of CC-CC and CC-CV charging methods

The two battery systems with sample A were arranged on the floor under a constant ambient temperature of 25 °C with sufficient distance between each battery to suppress the effects of battery heating. One system was charged with CC-CC and the other with CC-CV, as shown in Fig. 2.

Charging with CC-CV caused the temperature to rise to around 50 °C just after the change from CC to CV with gradual decrease of the charging current to almost zero. On the other hand, charging with CC-CC showed only a slight increase of the temperature to 42 °C just before the end of charging. All the batteries in the systems experienced almost the same temperature during both charging procedures because of the space between the batteries.

Charging with CC-CC prolonged cycle life further than that with CC-CV, as shown in Fig. 3. Charging with CC-CV

reduced the discharge capacity to less than 48 Ah over only 175 cycles in discharge both with constant current and with the SFUDS pattern, and finally, the cycle test finished at 202 cycles with discharge capacity reduction. On the other hand, charging with CC-CC slightly increased the discharge capacity until 150 cycles. After that, it gradually decreased to less than 48 Ah over 300 cycles. The capacity measurement of each battery after the cycle-life tests showed no excessively degraded battery in either system.

In the case of the system tested by charging with CC-CV, the reduction in discharge capacity is attributed to the capacity loss of the positive electrode on the basis of the results of measurement of the discharge voltage of the battery cells with a reference electrode of $Cd/CdSO_4$. SEM observations of the electrodes in the batteries after cycle-life tests (202 cycles) revealed degradation of the positive electrode due to softening of the active materials with high porosity and particle agglomeration (Fig. 4). The heating of batteries makes the potential of oxygen gas evolution lower than the constant voltage predetermined in the charge condition [6]. Charging with CC-CV did not decrease the amount of current so rapidly for it to have excess charging capacity for a few hours after the voltage rose to the predetermined constant voltage. Then, the excess capacity caused oxygen evolution at the positive electrode. The transport of oxygen gas, which was evolved at the positive electrode, to the negative electrode accelerated the heating of the batteries due to the exothermic recombination reaction of oxygen and hydrogen on the neg-

Fig. 4. Electron micrographs of the positive electrodes of sample A: (1) after charging with CC-CV for 202 cycles, and (2) as received.
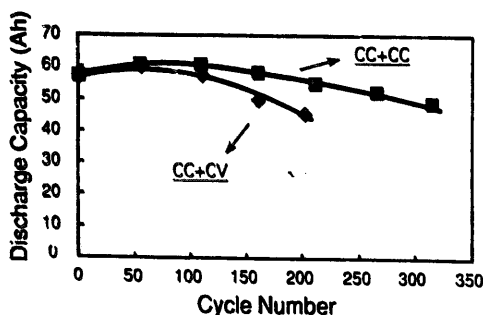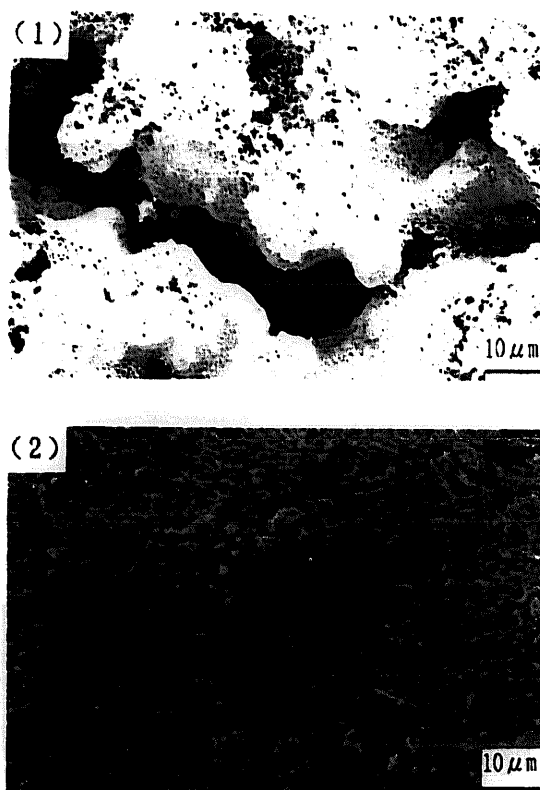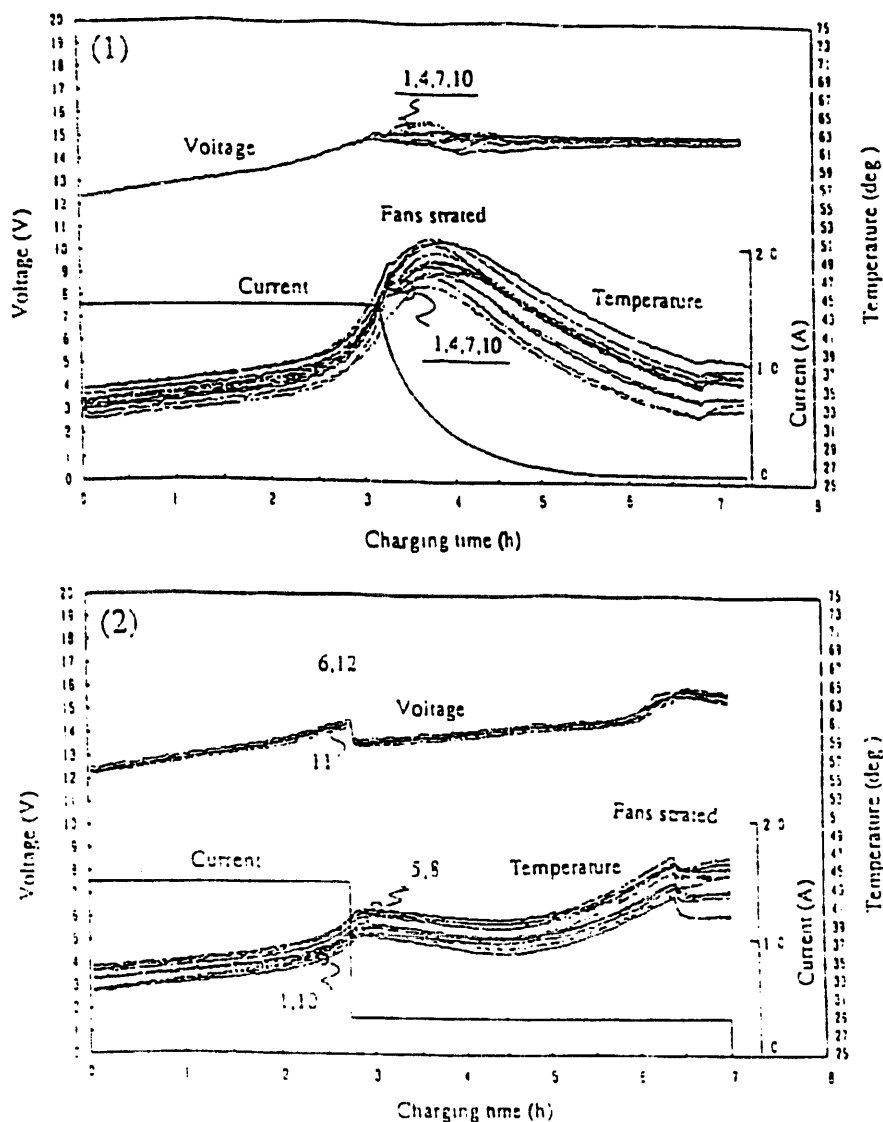

Fig. 3. Discharge capacity measured with constant current in cycle test for the battery system with sample A in charging with (◆) CC-CV and (■) CC-CC.

Fig. 5. Charging profiles of the battery system with sample B in battery boxes at the 100 cycle: (1) CC–CV, and (2) CC–CC.

ative electrode. Oxygen gas evolution causes softening of the high-porosity positive-electrode material.

The discharge capacity of the system tested by charging with CC–CC decreased to less than 48 Ah over about 300 cycles. In the measurement of discharge voltage, the degraded battery with the least discharge capacity in the system showed a rapid potential drop relative to the reference electrode in the measurement of discharge voltage. At the bottom of the negative electrode, more $PbSO_4$ products were measured by chemical analysis and during the SEM observation, many cubic particles, which were considered to be $PbSO_4$ particles, appeared. The separators contained a higher concentration of H_2SO_4 at the bottom than at the top. Concentration gradients from the bottom to the top were formed in long cycle-life tests. The concentration gradient reduced the charge capacity locally and enhanced the amount of products of $PbSO_4$ at the bottom of the negative electrode; then the discharge capacity of the cell gradually decreased. This result suggested that it

is necessary to maintain a uniform concentration of H_2SO_4 in the separator in order to further prolong cycle life.

3.3. Effect of the battery system environment on cycle life

The two systems with sample B arranged in battery boxes (Fig. 1) were charged with CC–CC or CC–CV. The battery systems were cooled by fans which were activated when the battery temperature exceeded 45 °C and stopped when it fell below 35 °C.

The profiles for charging with CC–CV showed that the temperature rose rapidly from room temperature when the predetermined voltage was approached (Fig. 5). The temperature reached a maximum of about 50 °C 1 h after CV charging started. The use of fans expanded the distribution of battery temperatures from 5 to above 10 °C. A slight rise of the temperature to 45 °C in the last part of charging with CC–CC required fan operation for only 1 h (Fig. 5).
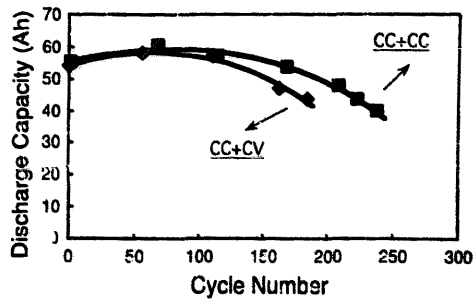
Fig. 6. Discharge capacity measured with constant current in cycle test for the battery system with sample B in battery boxes in charging with (◆) CC-CV (diamonds) and (■) CC+CC.

Charging with CC–CV in a battery box reduced the discharge capacity to less than 48 Ah over about 150 cycles (Fig. 6). The measurement of the discharge capacity of every battery following cycle life tests (183 cycles) showed that ' ʌ boxed batteries near the fans were degraded and exhibited reduced discharge capacity and weight loss of 250 g but that others still had more than 50 Ah discharge capacity. The discharge voltage curve of the reference electrode indicated that both electrodes were degraded in batteries near the fans. The softening of the positive electrode was observed by SEM, due to oxygen evolution by excess charging during CV charging. The charged negative electrode was found to contain $PbSO_4$ by means of EPMA observation (Fig. 7 (a)). The degraded batteries near the fans were cooled to a lower temperature than that of the other batteries. Cooling of batteries enhances the voltage ascent. Therefore, the batteries tended to have insufficient charge capacity, because the charge capacity was consumed for the electrolysis of water. Insufficient charging caused sulfation production of $PbSO_4$ in the negative electrode. The reduction of charge capacity corresponds to degradation of the negative electrode due to the sulfation products of $PbSO_4$ and the loss of water.

The cycle test in charging with CC–CC finished after 237 cycles due to a reduction of discharge capacity in the SFUDS pattern discharge on the cycle test. The softening of the positive electrode was not accelerated by cooling in charging with CC–CC, which is identical to that observed with CC–CV. The reduction of discharge capacity was due, howeve;. to a slightly insufficient charge caused by the faster ascent of charging voltage and the corrosion of grids in the positive electrode caused by deeper discharge in the cooled batteries (Fig. 7(b)).

These results suggest that it is more important to maintain a uniform environment inside the battery box than to create a cooler battery environment in order to achieve a prolonged cycle life.

3.4. Effects of the first constant current rate on cycle life

The battery systems of sample C could be charged in less than 8 h with both 0.2C and 0.5C (Fig. 8). The increase in charge current rate appreciably prolonged the cycle life
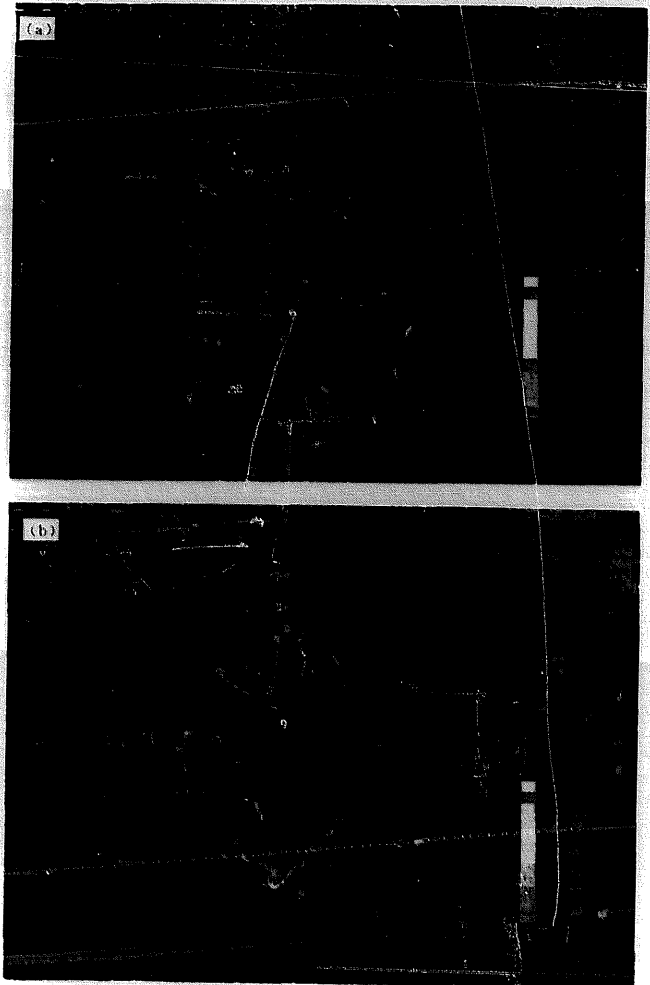

Fig. 7. EPMA observation of micrographs in cross section of electrodes in the module of no. 4 in the systems after charge. White dots indicate the existence of sulfur in the electrodes. The diamonds in the electrodes are grids. (a) Negative electrode after 183 cycles of cycle life test in charging with CC–CV. (b) Positive electrode after 237 cycles of cycle life test in charging with CC–CC.

(Fig. 9). The high rate of charge current with shortened charging time on the first step enhanced the energy efficiency by about 2% during discharge/charge. The predetermined constant voltage did not increase in relation to the higher ratio current, which prevented the batteries from wastefully undergoing the exothermic reaction.

Charging with a higher ratio current of the first charge in CC–CC prolonged the cycle life by preventing the positive electrode from softening due to material particle growth (Fig. 10). In 224 cycles of charging with 0.2C (12 A) in the first step in CC–CC, the material particles in the positive electrode grew up from less than 1 μm to more than 10 μm, which enhanced the positive electrode softening, while, the positive electrode contained material particles with a size of less than 1 μm before the cycle test. However, no growth of particles in the positive electrode was observed after 280 test cycles by charging with a higher ratio current of 0.5C (30 A), and several particles remained smaller than 1 μm after the cycle test. The capacity of the system decreased due to
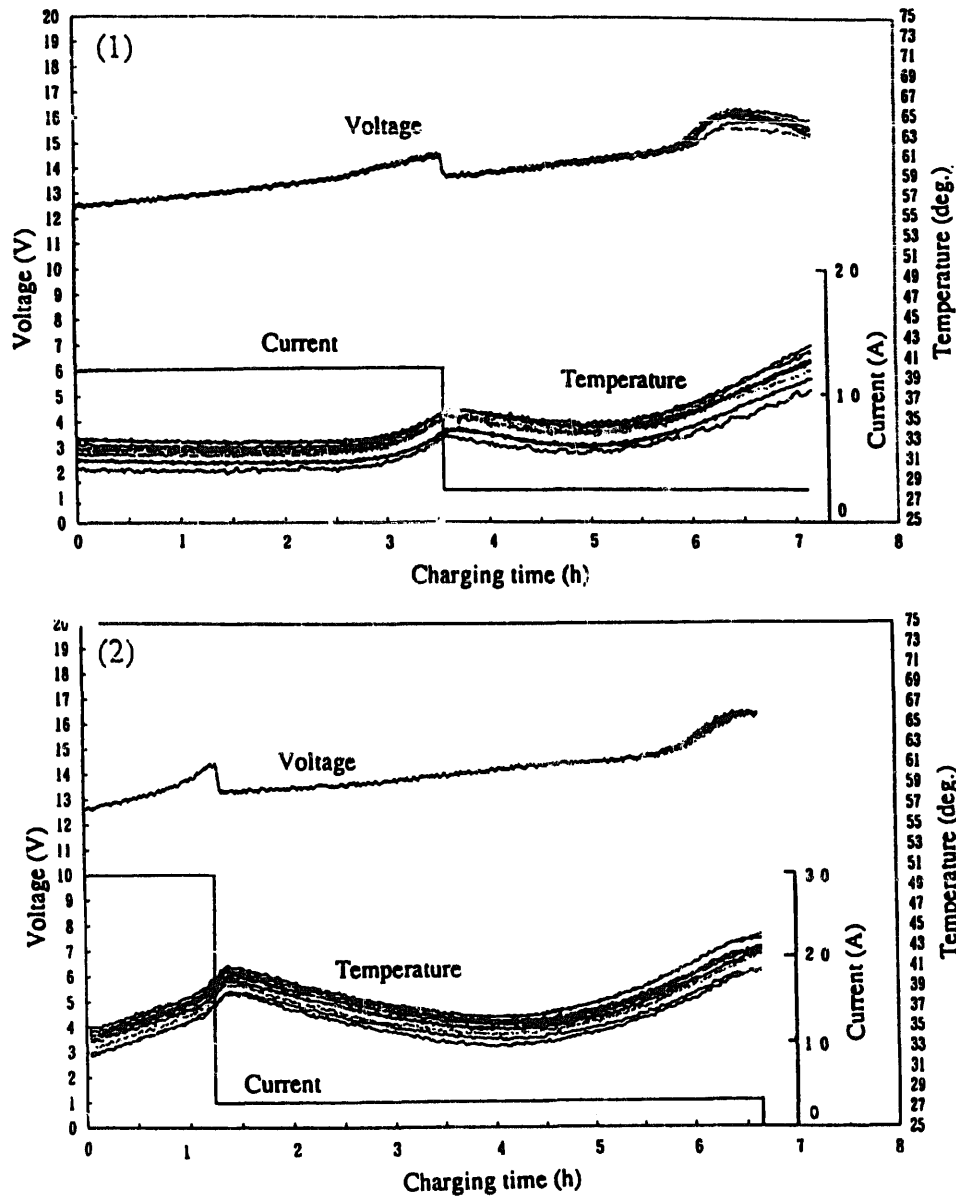
Fig. 8. Charging profiles of the battery system with sample C at the 100th cycle: (1) CC (0.2C)–CC (0.05C), and (2) CC (0.5C)–CC (0.05C).
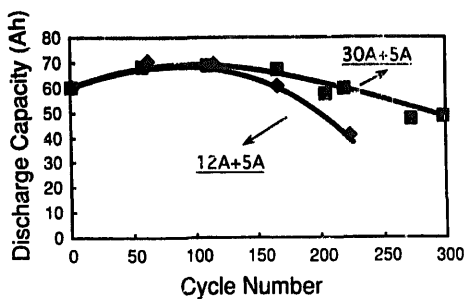

Fig. 9. Discharge capacity measured with constant current on cycle life test for the battery system with sample C in charging with CC–CC with the first constant current of (◆) 0.2C and (■) 0.5 C.

the degradation of some cells by internal short circuits caused by softening of material during the long cycle-life test. This result suggests that charging with the high-ratio current in the

first step of CC–CC shortens the charging time and prolongs cycle life by suppressing particle growth in the positive electrode. It will help to warrant the increase of night-time electric load.

The material particles in the positive electrode generally grow larger by decreasing the surface area and stabilizing the potential in cycle tests of lead/acid batteries [7], but the high rate of current charging in CC–CC suppressed the particle growth in this work. The rate of the formation of PbO_2 nuclei is higher than that of PbO_2 crystal growth in a lead/acid battery [8]. The higher rate of charging current will improve the nucleation rate for PbO_2, so that numerous small PbO_2 particles will be formed without further growth. The fast reaction from $PbSO_4$ to PbO_2 is accelerated by a high rate of charging current. Then, the concentration of H_2SO_4 temporarily increases partially around the active materials in the

Fig. 10. SEM micrographs of the positive electrodes: (1) after charging with CC (0.2 C)–CC (0.05 C) for 224 cycles, (2) after harging with CC (0.5 C)–CC (0.05 C) for 280 cycles.

positive electrode. The formation of small PbO_2 particles is stabilized by a higher concentration of H_2SO_4 [8,9]. In addition, small PbO_2 particles can be stably formed with water and hydrogen [10] because the formation reaction occurs very rapidly by virtue of the higher current rate that is used in charging. The mechanism of the suppression of particle growth by charging with a higher current rate should be more thoroughly studied in order to draw further conclusions.

3.5. Exchange of degraded batteries in the system

When EVs become popular in the future, it may be possible to exchange several degraded batteries in the battery system for good new ones in order to achieve economical EV maintenance.

After cycle testing, the discharging capacity of every battery of the battery system was measured. From the results, three degraded batteries with less than 45 Ah, one less degraded, and an average battery were selected for analysis of the degradation mechanism. Then, a renewed battery system was constructed using seven old batteries and five new replacements (nos. 2, 3, 7, 9 and 10). This system was discharged according to the SFUDS pattern and charged with both CC–CC and CC–CV.

In the system charged with both CC–CV and CC–CC, a different voltage behaviour is observed for old and new batteries (Fig. 11). In charging with CC–CC, both old and new batteries show identical voltage behaviour during the first step, but the voltage of the new batteries increases more than that of the old ones near the end of the second step. Some of the old batteries in the system are overcharged and overdischarged because the charging regulation is determined by the total voltage. The discharge capacity of the system rapidly decreases because it is governed by the discharge capacity of only the old batteries. This result is consistent with the findings of Peron and Symon [11] by simulation for batteries in connection.

4. Summary

EV battery systems with VRLA batteries can be charged by CC–CC and CC–CV in less than 8 h, which increases night-time load. The cycle life was longer with CC–CC charging than with CC–CV. A higher rate of charge current during the first step in the CC–CC charging prolongs cycle life due to suppression of the growth of active material particles in the positive electrode.

Control of the environment of battery boxes is very important in securing good cycle life. Cooling of parts of the battery systems by using fans reduced the discharge capacity of the systems, because these batteries tended to have insufficient charge capacity due to the negative electrode degradation caused by the sulfation products of $PbSO_4$.

VRLA batteries still do not have sufficiently long cycle lives for EVs to become more popular than internal combustion-engined vehicles. Therefore, it is necessary to continue the advancement of VRLA batteries with the aim of prolonging cycle life and improving performance. This must be conducted in cooperation with battery manufacturing companies.

In the next phase of the collaboration, a study will be made of methods that will charge in less than 8 h and will prolong the cycle life of EV batteries, and of charging with a few steps of constant-current charging, by varying the charging procedure, with the current and time for each step as control parameters.
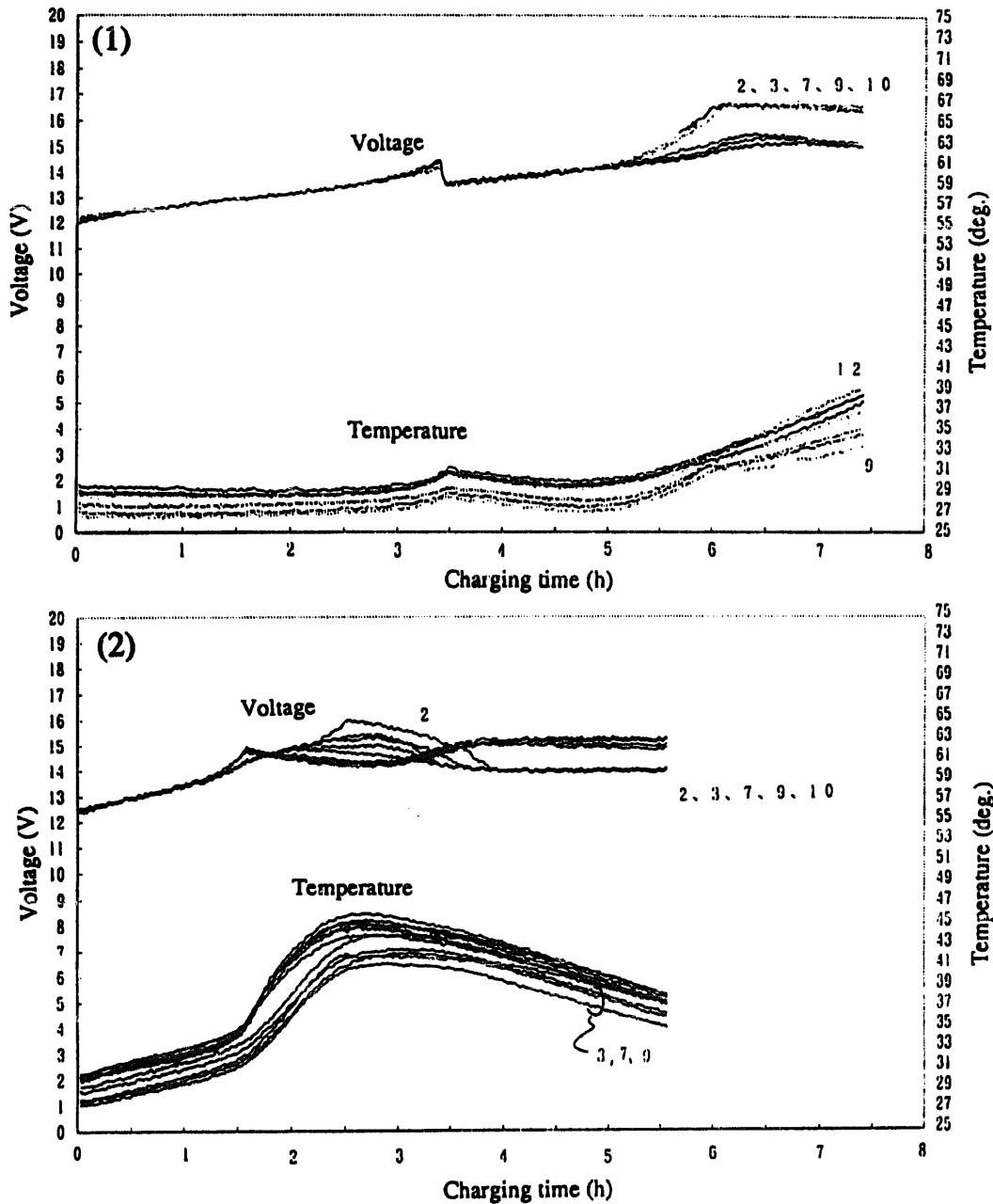
Fig. 11. Charging profiles of the renewed battery system with five new batteries of sample A: (1) CC–CC, (2) CC–CV.

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