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Journal of Power Sources 75 (1998) 101–107

JOURNAL OF POWER SOURCES

Multi-step constant-current charging method for electric vehicle, valve-regulated, lead/acid batteries during night time for load-levelling

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Received 12 March 1998; revised 24 March 1998; accepted 30 April 1998

Abstract

For the popularization of electric vehicles (EVs), the conditions for charging EV batteries with available current patterns should allow complete charging in a short time, i.e., less than 5 to 8 h. Therefore, in this study, a new charging condition is investigated for the EV valve-regulated lead/acid battery system, which should allow complete charging of EV battery systems with multi-step constant currents in a much shorter time with longer cycle life and higher energy efficiency compared with two-step constant-current charging. Although a high magnitude of the first current in the two-step constant-current method prolongs cycle life by suppressing the softening of positive active material, too large a charging current magnitude degrades cells due to excess internal evolution of heat. A charging current magnitude of approximately 0.5 C is expected to prolong cycle life further. Three-step charging could also increase the magnitude of charging current in the first step without shortening cycle life. Four-or six-step constant-current methods could shorten the charging time to less than 5 h, as well as yield higher energy efficiency and enhanced cycle life of over 400 cycles compared with two-step charging with the first step current of 0.5 C. Investigation of the degradation mechanism of the batteries revealed that the conditions of multi-step constant-current charging suppressed softening of positive active material and sulfation of negative active material, but, unfortunately, advanced the corrosion of the grids in the positive plates. By adopting improved grids and cooling of the battery system, the multistep constant-current method may enhance the cycle life. © 1998 Elsevier Science S.A. All rights reserved.

Keywords: Lead/acid battery; Electric vehicles; Charging load-levelling; Cycle life; Energy efficiency

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 in electric power supply management is how to increase the night-time electric load for the purpose of utilizing electric power generation equipment with high efficiency.

The popularization of EVs will warrant the increase of night-time electric load in Japan since EV batteries can be

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PII S0378-7753(98)00102-5

charged during the night using available patterns. The patterns should provide complete charging in less than 5 to 8 h, and effectively increase the electric load in the minimum demand period between 2:00 and 5:00 am [1]. Therefore, we should develop a new charging pattern to complete charging of the EV battery system in a short time with multistepped and high-magnitude constant current.

Some vehicle manufacturers have proposed to produce and sell EVs with a new type of battery, e.g., a Ni/MH battery or lithium-ion battery, in the next few years, while lead/acid batteries may become popular in the near future due to the benefits of safety, easy maintenance, cost performance, and figure of merit (FOM) [2,3].

In 1995, 10 Japanese electric power companies and the Central Research Institute of Electric Power Industry (CRIEPI) started a three-year collaborative investigation of battery systems for EVs [4,5]. In the first year, the charging procedure for valve-regulated lead/acid batteries connected in series in EVs was evaluated for both nighttime load levelling and for prolonging cycle life. Charging in less than 8 h by the two-step constant-current method gave larger cycle life than that given by the constant-current and constant-voltage (CC&CC) method, due to suppression of the degradation of the positive electrode caused by softening of the active material. The use of a high magnitude for the first current in the two-step constant-current method prolongs the cycle life by suppressing the softening of positive active material due to active material particle growth [5].

In this study, we have varied the magnitude of the first-step current and multi-step patterns to investigate the multi-step constant-current method with shortened charging time, higher energy efficiency and longer cycle life compared with two-step constant-current charging.

2. Experimental

2.1. Valve-regulated lead / acid batteries

A battery system was constructed using 12 valve-regulated lead/acid batteries (12 V/60 Ah, type-A or -B standardized by JEVS) connected in series. Samples of two types of prototype batteries, samples A (type-A) and B (type-B) were donated by two Japanese battery manufacturing companies. The battery system was set in a battery box with four fans, which simulated the battery arrangement under the floor of EVs [4,5].

2.2. Discharge patterns

The battery systems were subjected to cycle-life tests. Discharge was according to the SFUDS pattern [6] under the conditions of a capacity of 48 A h or voltage of 84 V. Two kinds of discharge for the measurement of capacity were performed every 50 cycles. One was discharge with a constant-current of 1/3 C (20 A) under 118.8 V (9.9 V/module), and the other was subjected to a SFUDS-pattern discharge to less than 84 V. In these measurements, the systems were charged by the two-step constant-current method with the first constant current of 0.2 C (12 A) to a predetermined voltage (172.8 V), and the second constant current of 0.05 C (3 A) at a capacity corresponding to the preceding discharge capacity (Table 1).

2.3. Charge patterns

The charge conditions were set so as to achieve complete charging of the battery systems in less than 8 h under nighttime conditions. The battery systems with sample A were charged by the two- or three-step constant-current method with a high magnitude of constant current in the first step, and those with sample B were charged by stepped constant-current methods, as summarized in Table 1. Each step charging, except the last, was regulated by a voltage of 172.8, irrespective of the magnitude of the charging current, in order to suppress loss of water.

2.4. Definition of cycle life

In this study, the cycle life of the battery system is governed by three parameters: voltage, discharge capacity

Table 1
Conditions of charging and discharging of battery system

Charging conditions: each step is regulated by a voltage of 172.8 V; the last step of 3 A is regulated not by voltage but by capacity corresponding to the preceding discharge capacity			Discharge conditions
Magnitude of constant current	2-step	30A + 3A	(1) Cycle life estimation with SFUDS pattern regulated by capacity of 48 Ah or voltage of 84 V
	2-step	42A + 3A	
	3-step	30A + 12A + 3A	
	3-step	60A + 12A + 3A	
Multi-step	2-step	30A + 3A	(2) Capacity test every 50 cycles with SFUDS pattern and constant current
	3-step	30A + 12A + 3A	
	4-step	30A + 12A + 6A + 3A	
	6-step	30A + 18A + 12A + 9A + 6A + 3A	

with the SFUDS pattern [6], and constant current. The cycle life test of the battery was terminated when any battery in the system showed a voltage decrease to zero upon discharge, a decrease in the discharge capacity (measured from the SFUDS pattern every 50 cycles) to less than 80% of the first discharge capacity, or a decrease in discharge capacity obtained with constant current to less than 49 A h [4].

On completion of the cycle life test, the discharge capacity of every battery in the system was measured with constant current down to 9.9 V/module. Some batteries were disassembled and analyzed by XRD, SEM, EPMA, porosimetry and chemical analysis methods in order to elucidate the degradation mechanism(s).

Table 2
Effect of the magnitude of the first-step current in the two- and three-step constant-current charging methods on the performance of Type A batteries

Charging pattern	Charging time (min)				Energy efficiency (%)	Cycle life
	First	Second	Third	Total		
12A + 3A (*)	213	217		430	73.0	221
30A + 3A (*)	76	340		416	75.1	299
30A + 3A	71	357		428	75.3	299
42A + 3A	47	405		454	77.3	260
30A + 12A + 3A	74	32	198	304	76.0	363
60A + 12A + 3A	32	57	190	279	76.9	360

At 200th cycle during cycle life tests.
The batteries were set on the floor as described in Ref. [4]).

3. Results and discussion

3.1. *Effect of the magnitude of the first-step constant current in two- or three-step constant-current charging*

3.1.1. *Profile of two- or three-step constant-current charging*

Type A battery systems could be charged in less than 7 or 8 h by each method (Fig. 1 and Table 2). The magnitude of the first-step current did not directly affect the shortening of total charging time, because a longer time was required in the second-step charging. By contrast, the charging time was shortened by increasing the number of steps from two to three in the constant-current charging methods, rather than by charging with a current of higher magnitude in the first-step.

The profiles show that a higher current in the first step widened the distribution of battery temperature (Fig. 1). A

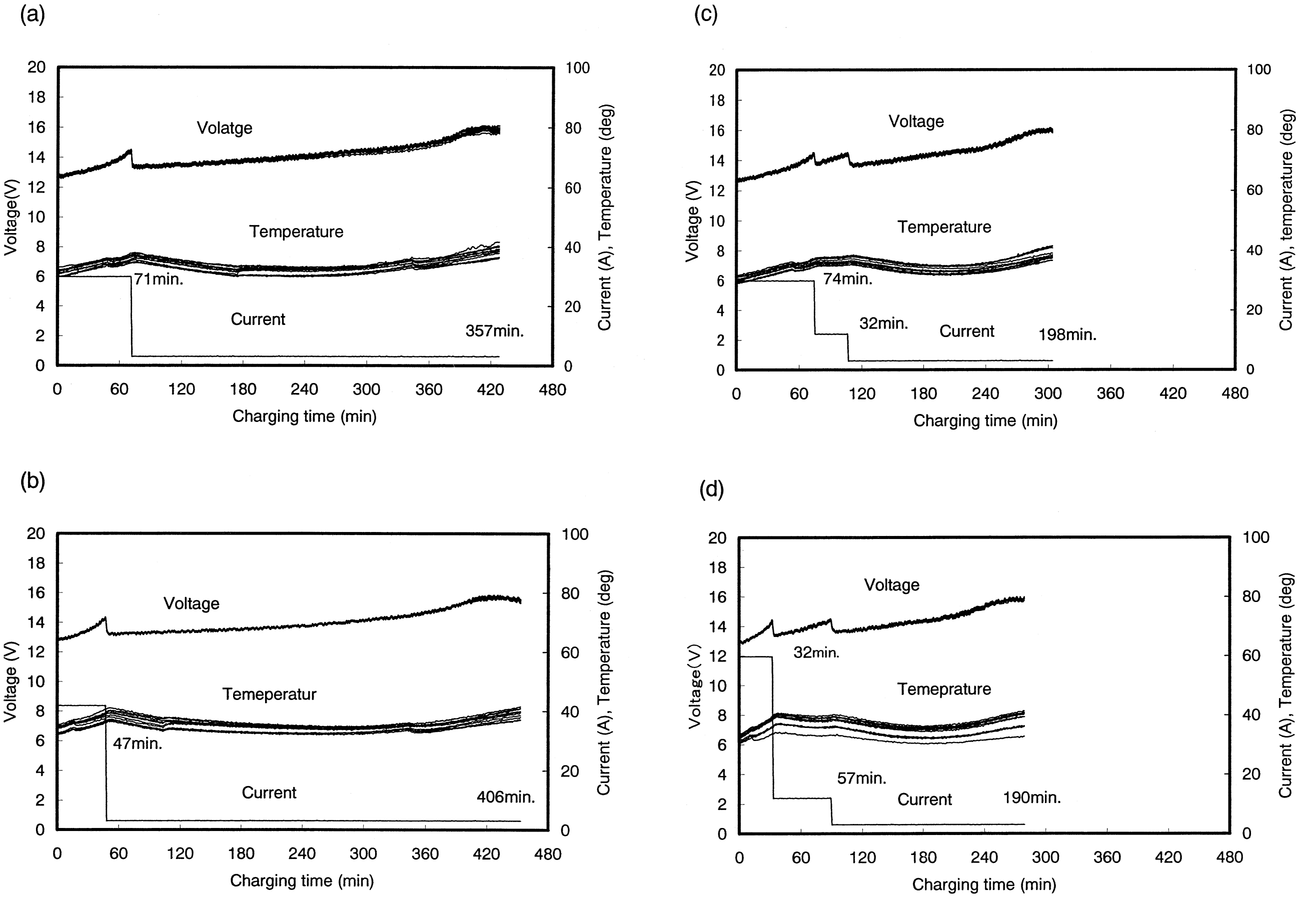

Fig. 1. Charging profiles, voltage, current and battery temperature of Type A battery system at 200th cycle. Two-step charging: (a) with 0.5 C + 0.05 C; (b) with 0.7 C + 0.05 C. Three-step charging: (c) with 0.5 C + 0.2 C + 0.05 C; (d) with 1.0 C + 0.2 C + 0.05 C.

Table 3
Summary of analytical results for modules under charging with high-rate current

Magnitude of charging	Small			Large	
Current (A)	12	30	42		(2-step)
		30		60	(3-step)
Cycle life	211	299	260		(2-step)
		363		360	(3-step)
Battery temperature distribution	low			high	
	narrow	wide	wide		(2-step)
		narrow		narrow	(3-step)
Discharge capability					
Low rate	Positive	Positive	Positive		(2-step)
		Positive		Positive	(3-step)
High rate	Negative	Negative	Negative		(2-step)
(limited electrode)		Negative		Positive	(3-step)
Positive electrode softening	Yes (large particle growth)			No	
Corrosion of grids	No	No	Yes	Yes	
Negative electrode					
Sulfation	slight	No	No	No	

slightly higher temperature occurred with a current magnitude of 0.7 C (42 A) at the end of the first-step charging than with a current of 0.5 C (30 A) in the two-step constant-current method. The temperature decreased to 35°C by operating fans during the second-step charging. A current of 0.7 C resulted in a longer charging time for the second step and higher heat evolution around the last step than those with a current of 0.5 C, because the amount of charge with a current of 0.7 C is not as high as that with 0.5 C when the regulated voltage is the same.

A current magnitude of 1.0 C (60 A) in the three-step constant-current method increased the temperature to 40°C in the first-step charging, which is higher than that of 0.5 C, but the temperature gradually decreased during the third-step charging to below about 35°C, which is as low as that with 0.5 C. Three-step charging with a current magnitude of 1.0 C took no longer than that with 0.5 C. The large magnitude of the first-step constant current resulted in the batteries being heated to a higher temperature due to the influence of the internal resistance.

3.1.2. *Discharge / charge energy efficiency*

The larger the magnitude of the constant current, the higher the charge–discharge energy efficiency. Generally, higher constant-current charging decreases energy efficiency. Generally, higher constant-current charging decreases energy efficiency, but in this study, the regulated voltage was fixed independent of the charging current to avoid energy loss by overcharging (Table 2). In a multi-step constant-current method, sufficient capacity can be obtained in the last charging step without voltage regulation.

3.1.3. *Cycle life*

In the two-step constant-current method, the first constant-current magnitude of 0.5 C produces a longer cycle life than in the case of either 0.2 C or 0.7 C. The higher rate of the first constant current in the two-step constant-current method prolongs the cycle life [2]. A current magnitude higher than 0.5 C in the first step does not, however, lead to a longer cycle life due to heat evolution by internal battery resistance during charging (Table 3). These results suggested that the optimal first-step current in the two-step constant-current method is around 0.5 C.

In the case of the three-step constant-current method, the magnitude of the first-step constant current has no effect on cycle life, as shown in Fig. 2. There is no difference in degradation for batteries charged with the

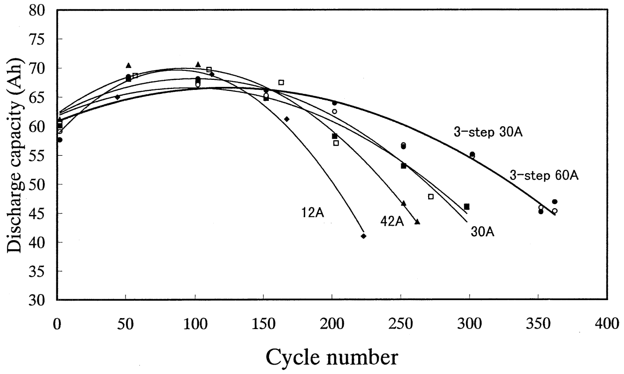

Fig. 2. Constant-current discharge capacity of battery system with two-step or three-step charging with high rate of current in cycle test.

first constant-current magnitudes of 0.5 C and 1.0 C, because the behaviour of heat evolution does not change due to the second step with the same magnitude of constant current in the three-step constant-current method. The three-step constant-current method does not result in as much excess heat evolution, as in the two-step method and, hence, battery degradation is less.

The results of analysis for the modules under charging with a high rate current are summarized in Table 3, and are used to elucidate the mechanism of degradation. Charging with a high-rate current suppresses the softening of positive active material [5], but a very high rate accelerates corrosion of grids in the positive plates. Therefore, discharging at a high rate was regulated by the positive electrode in the measurement of discharge capability. The sulfation can be decreased using a high-rate current due to long charging with a small current in the last step. Since charging with a high-rate current was regulated by a voltage of 172.8 V under all conditions, independent of the magnitude of the current, in order to suppress oxygen evolution at the positive electrode, the first and second steps could not provide charging to a sufficient capacity and the last charging step was prolonged.

An appropriate charging current of around 0.5 C is expected to extend the cycle life further. Also, multi-step charging with control of the lower voltage permits an increase of the magnitude of charging current in the first step without shortening the cycle life.

3.2. Effect of multi-step constant-current charging method

3.2.1. Profile of multi-step constant-current charging method

Type B battery systems can be charged in less than 8 h under each condition (Figs. 3 and 4 and Table 4). Multiple charging steps shorten the charging time, as shown in Table 4. The three-step method completed charging in 5.75 h, which is shorter than the two-step method by 75 min. The four-step method shortened the charging time by 50 min. On comparing the four- and six-step methods, it is found that the addition of two more steps has almost no effect on shortening the charging time, viz., only 14 min.

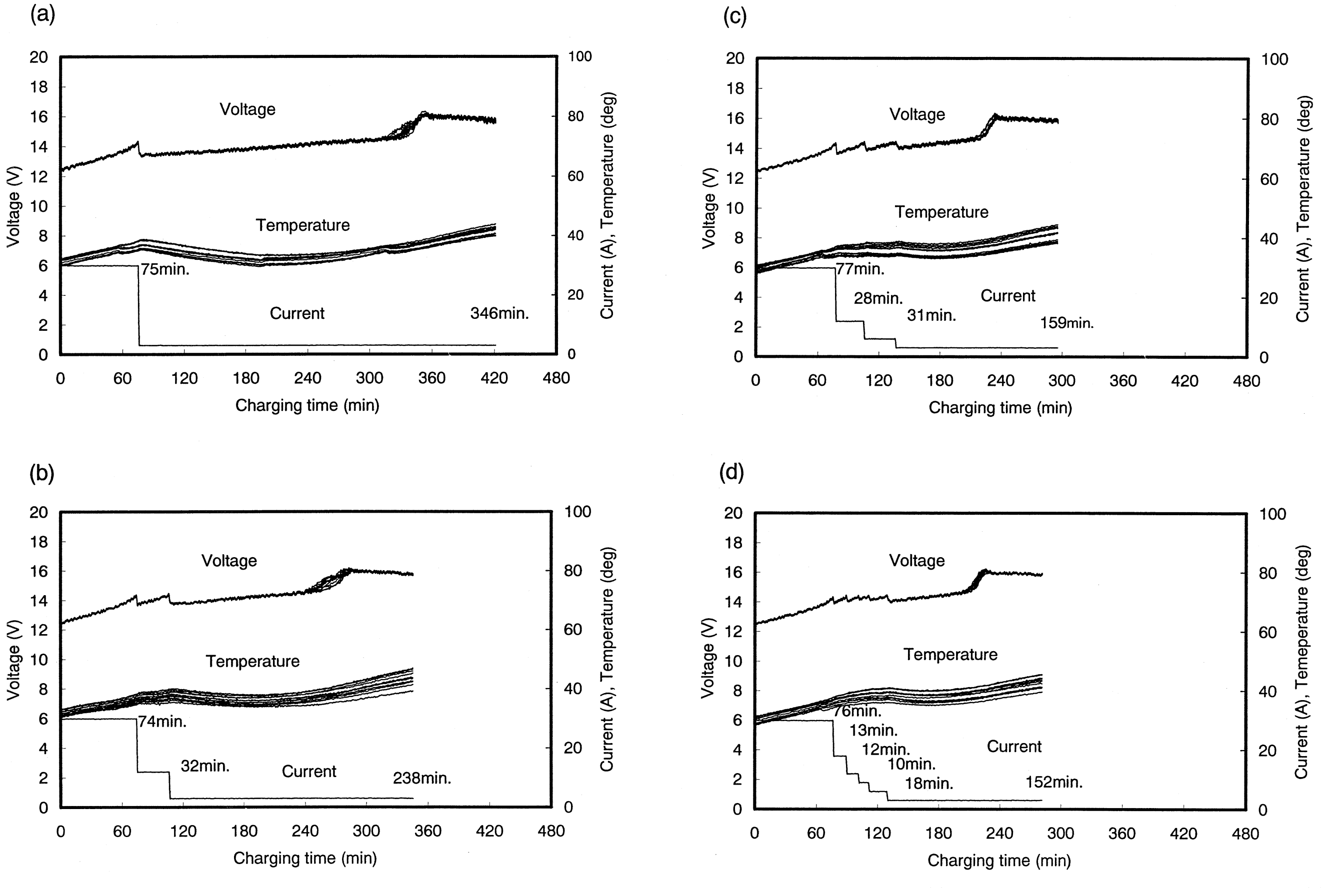

Fig. 3. Charging profiles, voltage, current and battery temperature of Type B battery system at 200th cycle: (a) two-step charging with 0.5 C + 0.05 C; (b) three-step charging with 0.5 C + 0.2 C + 0.05 C; (c) four-step charging with 0.5 C + 0.2 C + 0.1 C + 0.05 C; (d) six-step charging with 0.5 C + 0.3 C + 0.2 C + 0.1 C + 0.05 C.

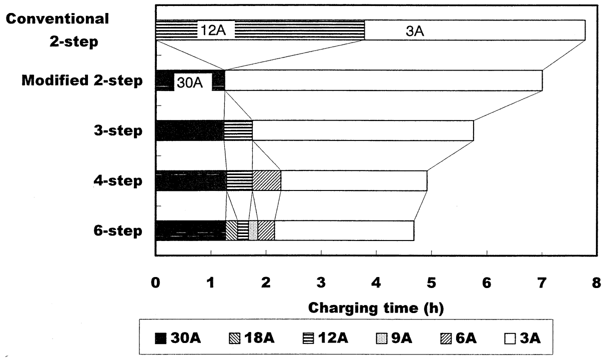

Fig. 4. Charging time under multistep constant-current charging.

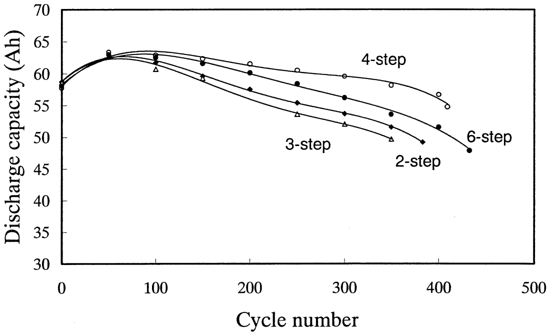

Fig. 5. Constant-current discharge capacity of battery system with multi-step charging.

The four- and six-step methods complete charging in less than 5 h (Fig. 4 and Table 4). The inclusion of a charging step with 6 A further shortens the charging time.

3.2.2. Discharge–charge energy efficiency

On multi-step constant-current charging, increasing the number of steps improves the energy efficiency. The last charging step is regulated, not by voltage, but by the total amount of charge. Only in the last step does the voltage exceed the regulated voltage of 172.8 V (14.4 V/module). The shortening of charging time in the last step improves the efficiency of charging and discharging, as shown in Table 4.

3.2.3. Cycle life

The cycle life obtained under each set of conditions with multistep constant current are shown in Fig. 5. The corresponding analysis results are summarized in Table 5, and are used to elucidate the mechanism of degradation.

A long charging time in the last step in the two- or three-step constant-current method causes the battery temperature to rise during charging. Excess heat evolution enhances the degradation of batteries. Numerous large pores are observed in positive plates on both types of battery by SEM imaging. Both battery types on subjecting to two- and three-step constant-current charging are degraded by softening of the positive active material. On the other hand, for batteries charged by the four- or six-step method, the grids around the top of the positive plate in a cell of the module can become broken during deep charging and discharging due to corrosion (Table 5).

Four- and six-step methods do not cause excess heat evolution during the last step, because they have many other steps with current magnitudes less than 0.5 C (30 A) and more than 0.05 C (3 A). Thus, the charging time for the last step can be shortened compared with the two- and three-step methods. The four- and six-step constant-current methods result in a longer cycle life of over 400 cycles compared with the two- and three-step methods. Unfortunately, the cycle life for the four-step method was interrupted due to heat evolution, for one of the twelve modules. The extrapolation of the cycle life curve in Fig. 5 indicates more than 500 cycles for the four-step constant current method.

The additional steps in the six-step constant-current method continuously maintain the voltage at around 172.8 V during charging, compared with the four-step method. The continuous maintenance of high voltage by increasing the number of charging steps causes the battery temperature to rise and expands the temperature distribution, and thus shortens the cycle life due to accelerated corrosion of the grids.

The multi-step constant-current method with four or six steps prolongs cycle life, improves efficiency, and shortens the charging time to less than 5 h. In general, the larger the magnitude of the constant current, the higher should be the regulated voltage, on account of the polarization of the electrodes, in order to achieve a sufficient amount of charge. In this study, the regulated voltage for each charging step was fixed in spite of increasing the magnitude of the charging current. The regulated voltage for every step was 14.4 V per module, which is the optimal regulated

Table 4
Effect of multistep constant-current charging on the performance of Type B batteries

Charging pattern (current)	Charging time (min)							Energy efficiency (%)	Cycle life
	30	18	12	9	6	3	Total		
30A + 3A	75					345	420	74.0	380
30A + 12A + 3A	74		31			240	345	74.8	354
30A + 12A + 6A + 3A	77		28		31	159	295	75.0	407
30A + 18A + 12A + 9A + 6A + 3A	76	13	12	10	18	152	281	75.0	432

At 200th cycle during cycle life tests.

Table 5
Summary of analytical results for modules charged with multi-step constant current

Number of steps	Few			Many
	Two	Three	Four	Six
Cycle life	380	354	407	432
Battery temperature	low			high
Temperature distribution	small			wide
Discharge capability				
Low rate	Positive	Positive	Positive	Positive
High rate (limited electrode)	Positive	Positive	Positive	Positive
Positive electrode				
Softening	Yes			No
Corrosion of grids	No	No	Yes	Yes
Negative electrode				
Sulfation	Slight	No	No	No

voltage for a current magnitude of 0.2 C (12 A). The condition with no increase of regulated voltage suppresses excess heat evolution and degradation of batteries by water loss, and maintains a slightly higher efficiency.

4. Conclusion

In two-step constant-current charging, a first-step with too large a current degrades cells through excess internal heat evolution, while a low current accelerates softening of positive active material due to growth of the PbO_2 particles. These results suggest that the optimal first-step constant current in the two-step method is around 0.5 C.

Multi-step constant-current charging further shortens the charging time and prolongs cycle life. Four-step constant-current charging with a first-step current of 0.5 C can be completed in less than 5 h with more than 400 cycles. Prolonged cycle life and a slightly high efficiency of charge and discharge can be obtained with a low regulated voltage for a large magnitude of the charging current in multi-step constant-current charging.

Future studies should study the effect of a fast-charging method on the EV battery system. In addition, a charging condition leading to high efficiency should be discussed in terms of the amount of charge and the last charging step in multi-step constant-current charging.

Acknowledgements

This study was conducted under the collaboration of a working group for the study of cycle life estimation of EV batteries under the Electric Vehicle Committee at the Central Electric Power Council. Parts of the work were presented at the poster session of EVS14 in Orlando, USA, December, 1997. We thank Japan Storage Battery. Matsushita Battery Industrial, and Yuasa for donating EV batteries and analyzing the degradation of batteries. The technical assistance of N. Kihira of CRIEPI and H. Hosoi of Denryoku Technical Engineering is gratefully acknowledged. We also thank Akagi Testing Center of CRIEPI for assistance with the experiments.

References

[1] E. Hayashi, T. Inasaki, F. Anan, Proc. of EVS12 at Anaheim, USA, 1994, p. 148.
[2] J.F. Cole, J. Power Sources 40 (1992) 1.
[3] P.T. Mosely, J. Power Sources 67 (1997) 115.
[4] T. Iwahori, Y. Ibi, F. Anan, Proc. of EVS13 at Osaka, Japan, 1996, Vol. 1, p. 97.
[5] T. Ikeya, M. Iwasaki, S. Takagi, Y. Sugii, M. Yada, T. Sakabe, E. Kousaka, H. Tsuchiya, M. Kanetsuki, H. Nasu, M. Ono, H. Narisoko, Y. Mita, K. Nishiyama, K. Adachi, T. Iwahori, J. Power Sources 69 (1997) 107.
[6] G.H. Cole, Proc. of EVS9 at Toronto Canada, 1988, EVS88-078.