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Estimation of the lifetimes of valve-regulated lead-acid batteries☆

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ABSTRACT

A method for estimating lifetime of valve-regulated lead-acid (VRLA) batteries used in float service under a variable-temperature environment was developed, and an effective means of shortening the period of an accelerated-lifetime test on a battery under cycle use was devised.

Battery lifetime in the case that the VRLA battery is used in float service at a constant temperature is estimated according to the results of high-temperature accelerated-lifetime tests. Actual ambient temperature surrounding a battery, however, changes significantly over the course of the year. The battery lifetime under such a variable-temperature environment is therefore estimated by summation of the deterioration degree at each working temperature. For this estimation, it is necessary to ascertain the "summation of deterioration degrees" at the different ambient temperatures at which the battery operates over a year. Accordingly, accelerated-lifetime tests under a constant temperature (65 °C) and under a 60/65 °C 4-monthly repeating cycle (i.e., 4 months at 60 °C, 4 months at 65 °C, and so on) at a constant float voltage 2.23 V were performed, and the expected lifetime at 25 °C was estimated from the lifetimes obtained from these test results. The estimation results show that both lifetimes are in fairly good accord. For that reason, even in the case that the battery is used under a variable-temperature environment, lifetime can be estimated by adding up the deterioration degrees at each temperature in the battery-operation environment.

For a lifetime test of a VRLA battery in cycle use, on the other hand, a considerable amount of time is required. Accordingly, aiming to shorten the lifetime-test period, we performed accelerated-lifetime tests by increasing the discharge current. To put that concretely, cycle discharge and charge tests were performed under either of two discharge conditions (0.35-h discharge at current of 1.0 CA: 35% depth of discharge and 2.3-h discharge at 0.23 CA: 53% depth of discharge), and charging to 104% of the discharged energy at four-step constant current. The results of these tests make it clear that the total discharge amount up until the end of battery lifetime is fairly consistent, regardless of the battery used as the test sample. For that reason, it is clear that by increasing discharge current used in a cycle lifetime test, it is possible to shorten the period required for the cycle lifetime test.

1. Introduction

In today's highly computerized society, communications lines must be sustained even in the event of an outage of the commercial power supply. Accordingly, as a means of supplying power to communications facilities and equipment during such a power outage, lead-acid batteries are generally used. For example, the number of sets of lead-acid batteries installed at facilities of NTT Group is approximately 30,000. Unlike a flooded-type lead-acid battery, the valve-regulated lead-acid (VRLA) battery does not require maintenance work such as re-filling with water. Moreover, the way in which it can be set up is unrestrained, and its lifetime has been extended through various developments [1,2]. Owing to these advantageous features, introduction of VRLA batteries is being speeded up.

The estimation of the battery lifetime in the case that the VRLA battery is used in float service at constant temperature was performed [3–5]. The lifetime of these VRLA batteries is correlated with ambient temperature: if the ambient temperature rises by 10 °C, the battery life (following the Arrhenius law) is cut by half [6]. In light of that fact, we performed accelerated-lifetime test in environments kept at constant ambient temperatures below 65 °C, and only batteries that have a favorable operating lifetime are introduced. Places where batteries are actually installed, however, rarely stay at constant ambient temperature throughout the year. Accordingly, it is necessary to consider a method for evaluating battery lifetime under actual utilization conditions (i.e., variable ambient temperature of the installation environment of the battery).

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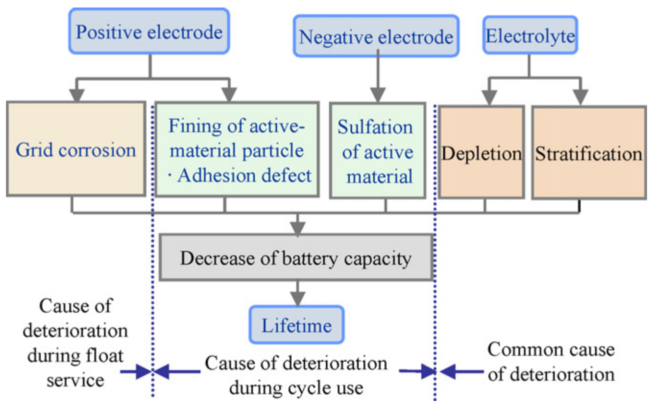

Fig. 1. Deterioration modes of valve-regulated lead-acid (VRLA) batteries.

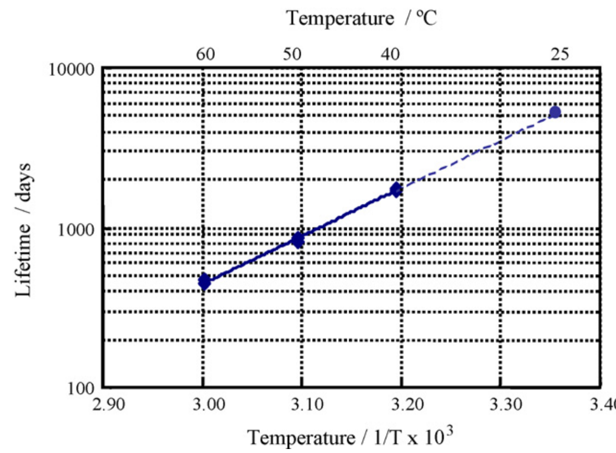

Fig. 2. Battery lifetime vs. ambient temperature.

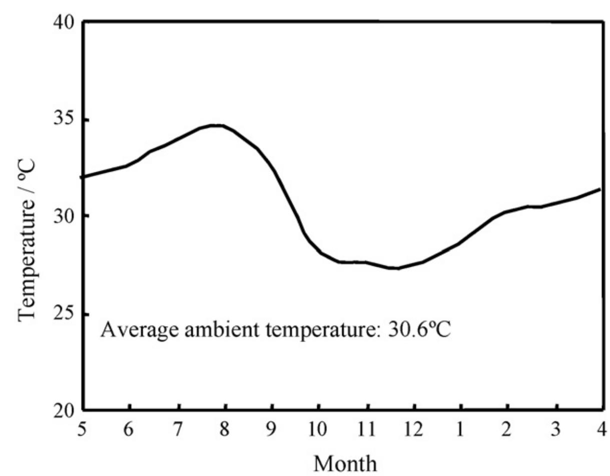

Fig. 3. Example of yearly temperature transition in a communications building.

What is more, electrical power consumption in today's Japan continues to rise year by year. Daily power consumption is, however, concentrated on daytime, so the power supply has a certain margin during nighttime. As a result, from the standpoint of effective utilization of power-generation facilities, it is desirable to level loads; power utilities thus supply electricity at a comparatively cheap rate during the nighttime hours. Given that circumstance, to level loads over the whole day and to effectively utilize cheaper energy during the nighttime, equipment for storing electrical energy is required. At NTT, we have developed an electric-energy storage system using VRLA batteries as a medium for storing electrical energy [7]. The VRLA batteries used in this electric-energy storage system are the "cycle use" type. Up until now, a method for evaluating the "cycle life" of a lead-acid battery in a short time period has not been available, so ascertaining the battery lifetime has needed a long time. For example, the LL1000-Ah battery, a product we developed, was designed to have an expected lifetime more than 3000 cycles at discharge current of 0.1 CA and depth of discharge (DOD) of 70%. However, confirming the battery lifetime under these conditions would take 8 years. In light of that fact, it was necessary to develop a method for evaluating the lifetime of a cycle use VRLA battery in a short time.

2. Conventional lifetime-evaluation methods

The main deterioration causes of VRLA batteries are shown schematically in Fig. 1. These causes can be divided into two main categories according to the usage mode, that is, float service deterioration or cycle use deterioration.

As for lead-acid batteries for backup power supplies of communications equipment, the main cause of deterioration is positive grid corrosion due to float charging. This positive grid corrosion depends strongly on the ambient environment around the battery; accordingly, when the temperature rises, the rate of corrosion increases. As a result, as a way of confirming battery lifetime in a short time, "high-temperature accelerated-lifetime testing" is used. Fig. 2 shows the results of such testing on a 2-V, 200-Ah VRLA battery at constant temperatures of 40, 50, and 60 °C. It is clear from this figure that when the ambient temperature rises by 10 °C, since a correlation (i.e., the Arrhenius law) that cuts battery lifetime by half comes into play, the lifetime at normal temperature (i.e., about 25 °C) can be estimated from the following equation:

$$L_{25} = L_t \times 2^{((t-25)/10)} \quad (1)$$

L_{25}: expected lifetime at 25 °C; L_t: lifetime obtained from accelerated-lifetime testing at t °C.

Fig. 3 shows an example of the yearly temperature transition in an NTT communications building. Since many communications building are not fitted with air-conditioners, the ambient temperature around batteries in those buildings is not constant throughout the year. Accordingly, to estimate the lifetime of a battery used in an environment under such a varying temperature, we consider the need to evaluate the degree of deterioration at each utilization temperature and sum up each degree.

As for "cycle use" like that used for batteries in electric-energy storage systems, it is thought the main causes of deterioration are as follows: fining of the positive active-material particle and adhesion defects, sulfation of the negative plate due to insufficient charging, and softening and depletion of active-material particles. In regards to these deterioration modes, since a means for evaluating lifetime in a short period in an "accelerated" fashion has not yet been established, repeated testing (under an actual specified charge-and-discharge pattern) over an extended period of time has been carried out up till now. In light of that circumstance, a method for evaluating lifetime in a short period of time has become much sought after.

3. Investigation on method for evaluating lifetime of lead-acid batteries for float service

3.1. Investigation method

In the case that the battery ambient temperature varies, with the aim of confirming the possibility of estimating the battery life-

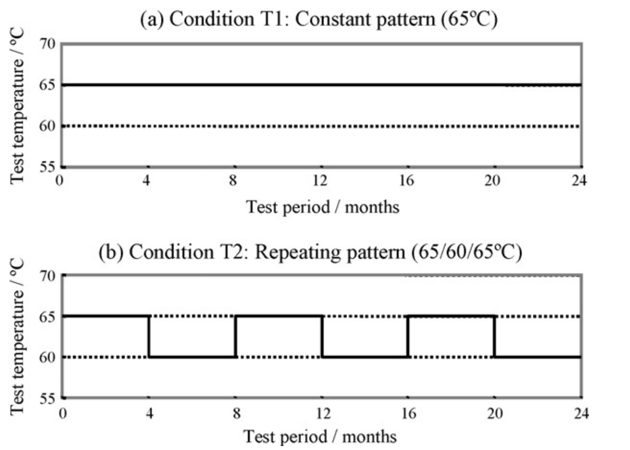

Fig. 4. Temperature patterns used for high-temperature accelerated-lifetime testing.

time by adding up the degrees of deterioration at each temperature, testing was performed under the following two conditions.

Under the first condition (hereafter, “condition T1”), high-temperature accelerated-lifetime testing was performed on a battery set up in a constant-temperature (65 °C) environment. Under the second condition (hereafter, “condition T2”), the testing was performed on a battery set up in a 4-monthly varying-temperature environment (i.e., 4 months at 65 °C, 4 months at 60 °C, and so on).

The respective temperature patterns for T1 and T2 are plotted in Fig. 4. During the high-temperature accelerated-lifetime testing, float charging is done at 2.23 V per cell constant voltage. Moreover, to confirm remaining capacity, every 2 months, the battery was placed in an environment at 25 °C, and its capacity was tested. And the lifetime at the point that the capacity drops below 70% of the initial capacity (and does not rise up again) was determined. Right before the capacity test was done, internal resistance of the battery was measured by the alternating-current method (at frequency of 1 kHz).

As a high-temperature accelerated-lifetime-test sample, a 2-V, 500-Ah VRLA battery which is typically installed at NTT communication facilities was used. Its specification is listed in Table 1. Moreover, for reasons of comparison, two different batteries, each constructed by a different manufacturer (hereafter, simply “company X” and “company Y”), were used. And two cells from each company’s test sample were selected.

3.2. Test results

3.2.1. Results of lifetime testing

Fig. 5 shows the results of high-temperature accelerated-lifetime testing on company X’s battery under conditions T1 and T2. Similarly, Fig. 6 shows the results of high-temperature accelerated-

Table 1
Specification of sample battery used for high-temperature accelerated-lifetime testing.

Item	Specification
Rated capacity (10-h rate)	500 Ah
Nominal voltage	2 V
Weight energy density	27 Wh kg^{-1}
Volume energy density	67 Wh L^{-1}
Usage ambient temperature range	−10 to 50 °C
Main application	Communication backup

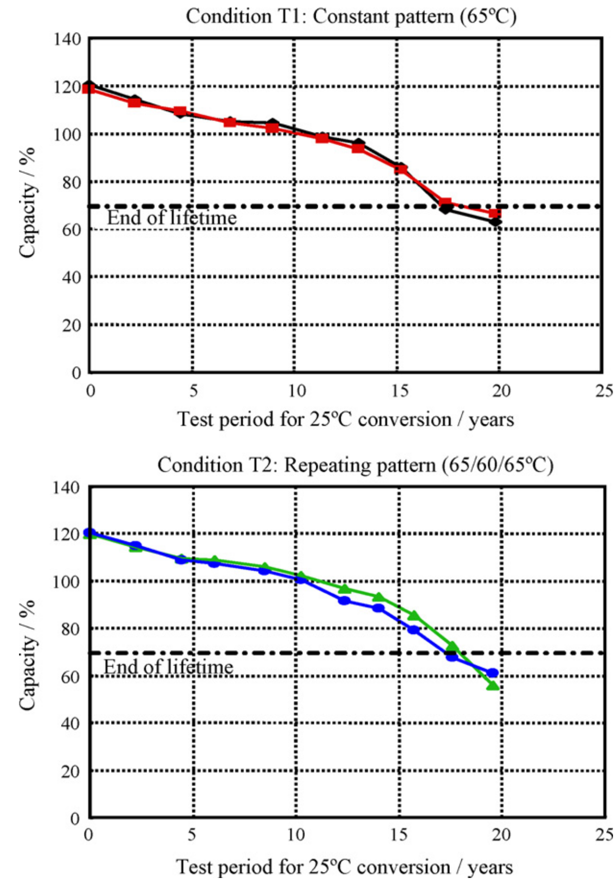

Fig. 5. Results of high-temperature accelerated-lifetime testing (Company X).

lifetime testing on company Y’s battery under conditions T1 and T2. In these figures, the horizontal axis plots the testing period converted to that a 25 °C equivalent by means of Eqs. (2) and (3) as follows:

$$L_{25T1} = L_{65T1} \times 2^{((65-25)/10)} \tag{2}$$

$$L_{25T2} = L_{60T2} \times 2^{((60-25)/10)} + L_{65T2} \times 2^{((65-25)/10)} \tag{3}$$

L_{25T1}: expected lifetime at 25 °C determined from condition T1; L_{25T2}: expected lifetime at 25 °C determined from condition T2; L_{65T1}: test period obtained from the testing at 65 °C under condition T1; L_{60T2}: total test period obtained from testing at 60 °C under condition T2; L_{65T2}: total test period obtained from testing at 65 °C under condition T2.

The lifetime at 25 °C under condition T1 (L_{25T1}) was calculated from the Arrhenius law given by Eq. (2) using lifetime L_{65T1} (i.e., the testing period up to the end of battery lifetime under a testing temperature of 65 °C) obtained under condition T1. Similarly, the lifetime at 25 °C under condition T2 (L_{25T2}) was calculated from Eq. (3) with L_{65T2} (sum of testing periods at test temperature of 65 °C up to the end of the battery lifetime) and L_{60T2} (corresponding sum of testing periods at test temperature of 60 °C) obtained under condition T2. These results are listed in Table 2.

According to these results, the average expected lifetimes at 25 °C of company X’s sample battery obtained from conditions T1 and T2 are in accord. Similarly, even though the error between the averages expected lifetimes of company Y’s sample battery is 2.8%, we can say that they are in fairly good accord, thereby making it clear that L_{25T1} equals L_{25T2}. This result means that it is possible to estimate the lifetime of a battery under a variable-temperature

Table 2
Results of high-temperature accelerated-lifetime tests.

Sample		Pattern				Error (%)
		Condition T1 (constant 65 °C)		Condition T2 (65/60/65 °C repeating)		
		25 °C-converted lifetime (years)	Average lifetime (years)	25 °C-converted lifetime (years)	Average lifetime (years)	
X	No. 1	17.3	17.8	18.0	17.8	0.0
	No. 2	18.3		17.6		
Y	No. 1	25.0	25.1	25.0	24.4	2.8
	No. 2	25.3		23.8		

environment by summing up the “degrees of deterioration (i.e., 25 °C-converted lifetime)” at each temperature.

3.2.2. Results on internal-impedance transition

The temporal changes in internal impedance of company X’s two sample batteries under conditions T1 and T2 are plotted in Fig. 7.

Similarly, the temporal changes in internal impedance of company Y’s two sample batteries under conditions T1 and T2 are plotted in Fig. 8. In these figures, the horizontal axis represents test period converted to 25 °C-equivalent test period by the same method using the lifetime-test results. Both the condition T1 impedance curves and the condition T2 impedance curves for sample batteries (i.e., company X’s and company Y’s) show a rising trend with little significant difference between numerical values. It can therefore be concluded that the deterioration can be summed up regardless of the test condition.

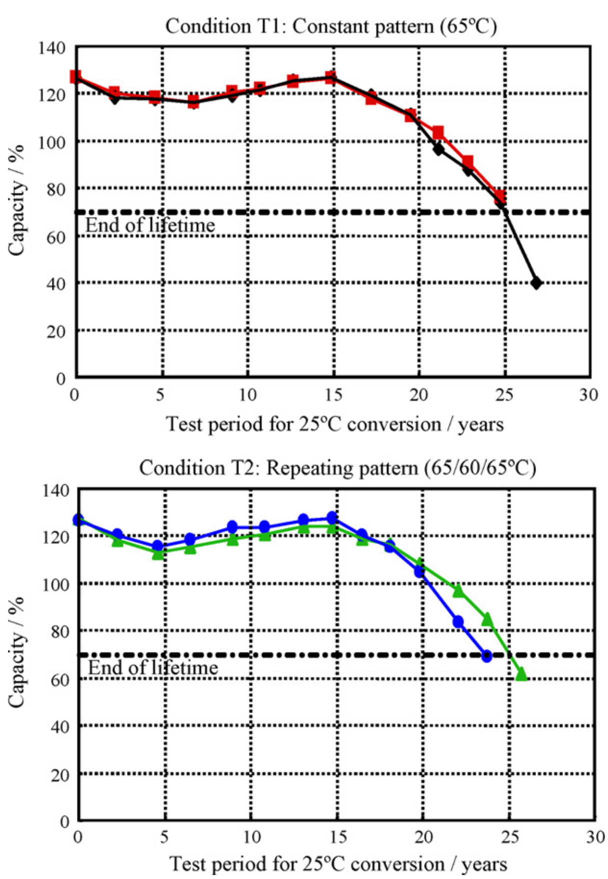

Fig. 6. Results of high-temperature accelerated-lifetime testing (Company Y).

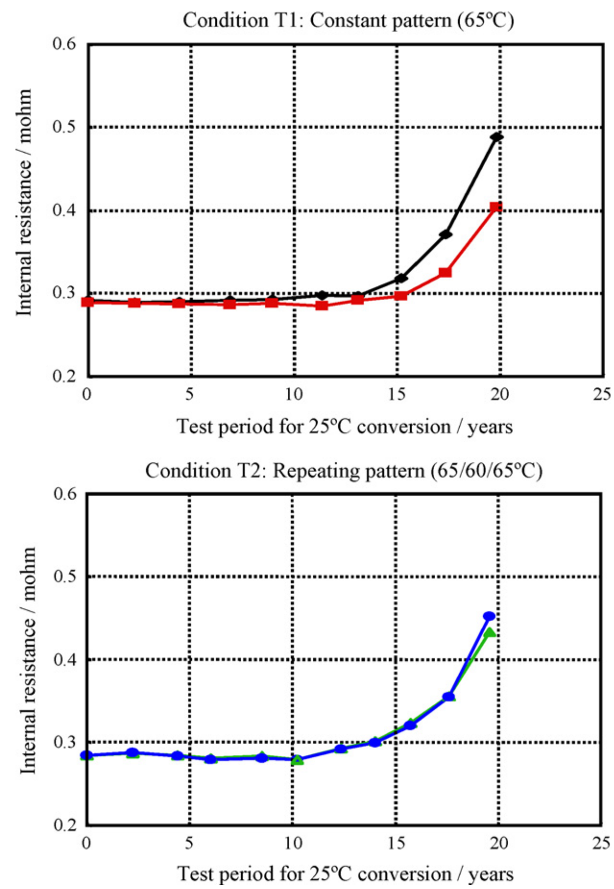

Fig. 7. Change of internal resistance (Company X).

4. Investigation on method for evaluating lifetime of lead-acid battery in cycle use

4.1. Test method

Aiming to confirm whether the accelerated-lifetime evaluation could be done in a short time when discharge current of the battery is increased, we performed the tests under the two test patterns described below.

The details of the test patterns (listed in Table 3), referred to as cycle-testing conditions C1 and C2, are as follows: (C1) discharging of 0.35-h at current of 1.0 CA (i.e., 35% depth of discharge corresponding to rated capacity) and charging to 104% of the discharged energy at four-step constant current and (C2) discharging of 2.3-h at current of 0.23 CA (i.e., 53% depth of discharge corresponding to rated capacity) and charging to 104% of the discharged energy at four-step constant current.

Figs. 9 and 10 respectively show the discharge-and-charge patterns under conditions C1 and C2. The ambient temperature of the

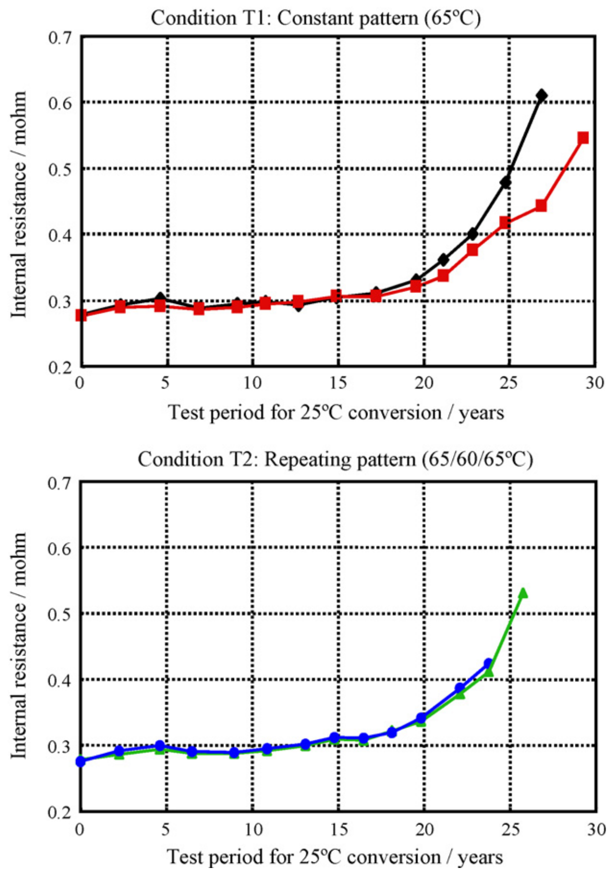

Fig. 8. Change of internal resistance (Company Y).

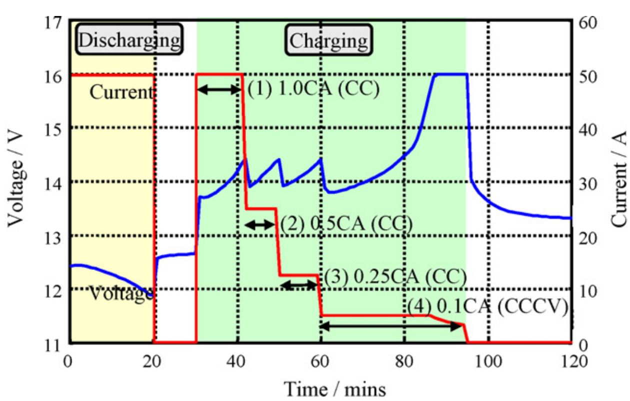

Fig. 9. Example of cycle-testing pattern (condition C1: 1.0-CA discharge).

Table 3
Cycle-testing pattern.

	Discharging			Charging	
	Current (CA)	Cutoff voltage (V)	Depth of discharge (%)	Pattern	Charging rate (%)
Condition C1	1.0	9.6	35	Four-step constant current (1) 1.0 CA (2) 0.5 CA (3) 0.25 CA (4) 0.1 CA	104% of discharged energy
Condition C2	0.23	10.2	53	Four-step constant current (1) 0.23 CA (2) 0.1 CA (3) 0.05 CA (4) 0.02 CA	104% of discharged energy

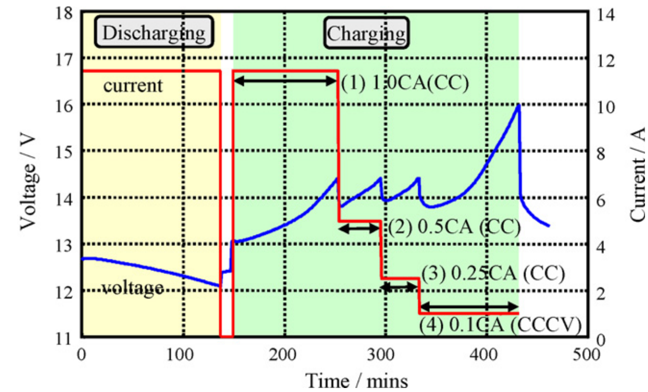

Fig. 10. Example of cycle-testing pattern (condition C2: 0.23-CA discharge).

Table 4
Main specification of sample battery for cycle testing.

Item	Specification
Rated capacity (10-h rate)	50 Ah
Nominal voltage	12 V
Weight energy density	20 Wh kg^{-1}
Volume energy density	63 Wh L^{-1}
Usage ambient temperature range	−30 to 50 °C
Main application	Energy storage system

battery during the test period was 25 °C. Once every 2 months, the battery was discharged to a cut-off voltage of 10.2 V at a current of 0.16 CA, and its capacity was ascertained. The point at which the capacity drops below 70% of the initial capacity (and does not rise up again) was defined as the battery lifetime.

As test samples, three 12-V, 50-Ah VRLA batteries (developed for small-capacity energy-storage systems) were selected, each by a different manufacturer (hereafter, companies K, L, and M), for the sake of performance comparison (see battery specification listed in Table 4).

4.2. Test results

The lifetime-test results for conditions C1 and C2 are shown respectively in Figs. 11 and 12. The cycle-usage lifetimes and total discharged ampere-hour up until the end of lifetime for each sample battery are listed in Table 5. The total discharged ampere-hours of the batteries under condition C1 (T_{C1}) and condition C2 (T_{C2}) were calculated respectively from Eqs. (4) and (5).

$$T_{C1} = L_{C1} \times 50 \times 0.35 \quad (4)$$

$$T_{C2} = L_{C2} \times 50 \times 0.53 \quad (5)$$

Table 5
Cycling test results.

Sample	Lifetime (no. of cycles)		Total discharged ampere-hour (Ah)		Total discharged Ah error (%)
	L_{C1}	L_{C2}	T_{C1}	T_{C2}	
Company K	7000	4800	122,500	127,200	3.8
Company L	6800	4830	119,000	127,995	7.6
Company M	8070	4920	141,225	130,380	7.7

Table 6
Cycling lifetime and total test period.

Sample	Lifetime (no. of cycles)			Total test period (h)			Ratio (%)	
	L_{C1}	L_{C2}	L_{C3}	$L_{C1} \times 1.35$ (A)	$L_{C2} \times 7.03$ (B)	$L_{C3} \times 17$ (C)	(A)/(B)	(A)/(C)
Company K	7000	4800	3500*	9450	33,744	59,500*	1/3.6	1/6.3*
Company L	6800	4830	3400*	9180	33,955	57,800*	1/3.7	1/6.3*
Company M	8070	4920	4035*	10,895	34,588	68,595*	1/3.2	1/6.3*

* Estimated values by calculation.

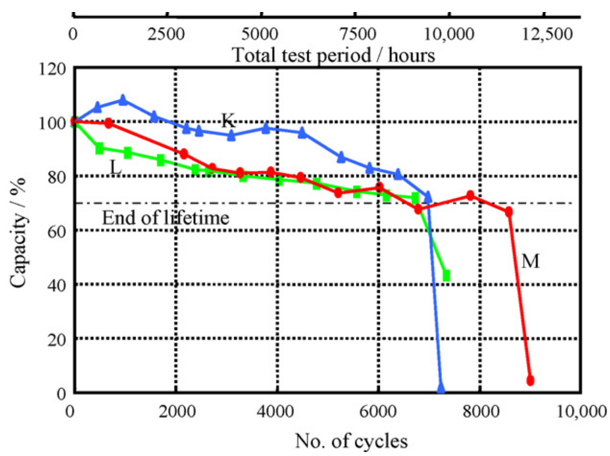

Fig. 11. Results of cycling lifetime tests (condition C1: 1.0-CA discharge).

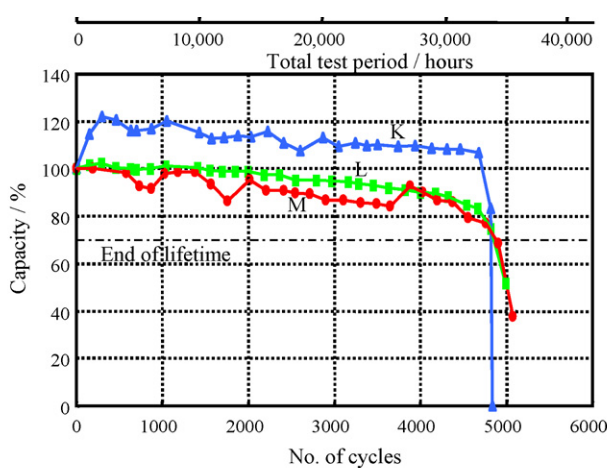

Fig. 12. Results of cycling lifetime tests (condition C2: 0.23-CA discharge).

50: Rated capacity of the sample battery (50-Ah); T_{C1}: total discharged ampere-hour calculated from condition C1; T_{C2}: total discharged ampere-hour calculated from condition C2; L_{C1}: cycle lifetime under C1; L_{C2}: cycle lifetime under C2.

Consequently, the total discharged ampere-hours of all the samples under either condition C1 or C2 are in fairly good accord, even though the maximum difference is about 7%. This result makes it clear that T_{C1} and T_{C2} are equal. What is more, in the case of these tests, it was assumed that the charged ampere-hour in each cycle was 104% of the discharged ampere-hour, so we can also say that the total charged ampere-hours under conditions C1 and C2 are also pretty much in accord.

The total test period was calculated from the product of the cycle lifetime and the time needed for one cycle of the discharge–charge tests. The calculation results are listed in Table 6. The times needed for one cycle under conditions C1 and C2 are given by Figs. 9 and 10, respectively, as 1.35 and 7.03 h. Note that downtime between switchovers from charging to discharging and from charging to discharging are not included in these times. It becomes clear from this result that by increasing discharge current during the cycle test from 0.23 to 1.0 CA, it is possible to shorten the test period by one third and, thus, estimate the cycle lifetime in a short time period. In addition, it is also clear that the cycle-lifetime number under different discharge current conditions can be estimated from the cycle-lifetime test results obtained by increasing discharge current.

Given the fact that total discharged ampere-hours are in fairly good accord even in the case of different discharge currents, cycle lifetime in the case that the cycle tests were performed under a standard-use condition (called "C3" here: discharge current of 0.1 CA and discharge depth of 70%) was calculated as L_{C3} from Eq. (6). Similarly, the estimated total test period was calculated from the product of L_{C3} and the time required for one cycle of the discharge–charge test (see Table 6). The time required for one cycle of under condition C3 was taken as 17 h according to the results of previous cycle tests [4].

$$L_{C3} = \frac{T_{C1}}{50 \times 0.7} \quad (6)$$

50: Rated capacity of the sample battery (50-Ah); L_{C3}: cycle lifetime under standard-use condition C3.

According to the results listed in Table 6, by increasing discharge current of the cycle test, it is possible to shorten the test period by 1/6.3 and thus estimate the cycle lifetime in a short time period.

5. Summary

The main results of these tests described in this report can be summarized by the following two main points.

First, accelerated-lifetime tests under a constant temperature (65 °C) and under a 60/65 °C 4-monthly repeating cycle (i.e., 4 months at 60 °C, 4 months at 65 °C, and so on) at a constant float voltage 2.23 V were performed, and the expected lifetime at 25 °C was estimated from the lifetimes obtained from these test results. Even in the case that a battery is used under a varying-temperature environment in float service, it is possible to estimate the expected battery lifetime by summing up degrees of deterioration, that is, lifetimes, at each usage-environment temperature.

Second, cycle discharge and charge tests were performed under either of two discharge conditions (0.35-h discharge at current of 1.0 CA: 35% depth of discharge and 2.3-h discharge at 0.23 CA: 53% depth of discharge), and charging to 104% of the discharged energy at four-step constant current. By increasing discharge current in a cycle lifetime test from 0.23 to 1.0 CA, it is possible to shorten the test period by one-third. And by increasing discharge current used in a cycle lifetime test from 0.1 to 1.0 CA, it is possible to shorten the test period by about one-sixth.

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