ELSEVIER

Journal of Power Sources 59 (1996) 171–175

JOURNAL OF POWER SOURCES

Valve-regulated lead/acid batteries for electric vehicles: present and future

K. Suzuki, K. Nishida, M. Tsubota

EV Battery Engineering Department, Japan Storage Battery Co., Ltd., Kyoto, Japan

Received 19 October 1995; accepted 13 November 1995

Abstract

In the USA, the State of California has officially planned to introduce zero-emission vehicles (ZEVs) in 1998. In Japan, Hino Motors, Ltd., has developed the HIMR bus as a low-pollution vehicle. Worldwide, vehicle developers are using valve-regulated lead/acid (VRLA) batteries as the power sources. This is because the technology has easy maintenance and good safety characteristics. The authors' company is working on the development of VRLA batteries and is continuing to improve them via feedback from both bench and field tests. By means of better positive plates, negative plates and separators, longer battery life has been achieved. This paper discusses the present status and future advancement of the VRLA batteries.

Keywords: Lead/acid batteries; Valve-regulated lead/acid batteries; Zero-emission vehicles; Electric vehicles

1. Introduction

In the USA, the State of California has officially planned to introduce zero-emission vehicles (ZEVs) in order to alleviate urban pollution from motor-vehicle exhaust emissions. Beginning in 1998, 2% of the motor vehicles sold within the State by the major suppliers must be ZEVs; the number will be raised stepwise to 10% in 2003. Automakers are developing strategies to implement the plan. Electric vehicles (EVs) are promising candidates for ZEVs.

Meanwhile, in Japan, Hino Motors, Ltd., has developed the HIMR bus, as a low-pollution vehicle. In this vehicle, the diesel–electric hybrid system converts braking energy into electricity and stores it in the batteries. During acceleration, the batteries assist the engine and, thereby, the system reduces emissions of black smoke and NO_x. Currently, about 100 of these buses are in service, mainly on city-bus routes in Tokyo and Osaka.

The authors' company is pursuing the development of valve-regulated lead/acid (VRLA) batteries for ZEVs and low-pollution hybrid buses. This paper reports progress and the direction that the battery development will take in the future.

2. ZEV batteries

2.1. Electric vehicles in Japan

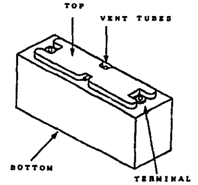
The status of EVs in Japan is outlined in Table 1. Those in general use are light vans. Including all types, there are about 2000 EVs in use. Almost all these vehicles carry 8 to 10

Table 1
Status of electric vehicles (EVs) in Japan

	EVs (at present)	EVs (developmental)
Vehicle type	Light vans (about 2000 vehicles) Daihatsu HIJET Suzuki carry van	Passenger cars
Motor	d.c.	a.c.
Batteries	Flooded lead/acid: 150 Ah, 96 or 120 V	VRLA: 60 Ah, 228 V
Maintenance	Water addition required	Water addition not required
Remarks	Explosions, leakage (electrical shock)	Explosions prevented by eliminating space under cover

Elsevier Science S.A.
SSDI 0378-7753(95)02319-4

Table 2
SAE/JEVS standard electric-vehicle battery

External dimensions	Length (mm)	388±2
	Width (mm)	116±2
	Height (mm)	175±2
External view		

flooded-electrolyte batteries with a C_5 capacity of 150 Ah. In general, charging is accomplished by a modified constant-voltage method. The batteries are replenished with water via topping-up devices that are moulded into the battery lids. Water is added once every two-to-four weeks, as dictated by the extent of the duty.

By contrast, the standard battery assembly for electric ZEVs now under development is 20 to 28 VRLA batteries of 60 Ah capacity ($C_3/3$ rate). In order to minimize electrolyte loss during charging, the batteries are charged with a two-stage, constant-current procedure or with a constant-current/constant-voltage schedule.

Given the expected increase in ZEV users, it is important that the batteries are easy to maintain and safe to use. For this reason, automobile manufacturers are conducting tests on VRLA batteries that do not require topping up, and that present little danger of explosions, shocks due to leaks, or other hazards.

2.2. *Standard size for batteries*

A unified standard has been established by the SAE and the JEVS. This prescribes the dimensions, shape and other features of EV batteries. The specifications are given in Table 2. These are: (i) the batteries are long with a low profile; (ii) the terminals are centred at the ends, and (iii) terminals are M8 bolts. These standards apply to all EV batteries, i.e. from VRLA batteries to new types of batteries.

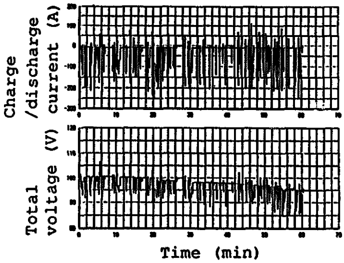


Fig. 1. Battery current and voltage characteristics during field tests.

2.3. *Specifications for standard-size GS batteries*

The VRLA battery is based on absorptive glass-mat (AGM) technology and uses polypropylene resin for its container and lid materials. Stainless-steel plates reinforce the battery ends so that adequate compression is maintained on the plate groups. Stainless-steel terminal bolts are used in the interests of both strength and corrosion resistance.

2.4. *Results of initial performance tests*

The results of the initial performance tests on a standard-size GS battery are presented in Table 3. The battery is superior to existing deep-cycle batteries in terms of energy density, high-rate discharge performance and, especially, specific power.

2.5. *Field tests*

The following conditions were used for the field test: (i) test vehicle: Daihatsu HIJET; (ii) test battery: eight VRLA batteries, 60 Ah ($C_3/3$ rate); (iii) test course: ordinary roads; (iv) distance travelled: about 20 km (80% of single-charge range), and (v) charging: two-stage, constant-current method.

The current and voltage characteristics when charging and running the vehicle are shown in Fig. 1. There is a maximum current of over 300 A. The C_3 (3 h rate) and $3C_3$ capacities at each 50 cycles of the field test are given in Fig. 2. After

Table 3
Initial performance test results of GS valve-regulated lead/acid battery

Model/performance parameter	Developmental	Conventional
$C_3/3$ capacity at 30 °C (Ah)	63	60
$1C_3$ discharge capacity at 30 °C (Ah)	46	42
$3C_3$ discharge capacity at 30 °C (Ah)	38	30
Specific power (W kg^{-1}) (JEVS method)	295	240
Specific energy (Wh kg^{-1})	34	30
Energy density (Wh l^{-1})	96	69

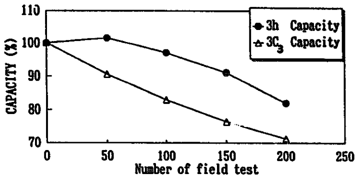


Fig. 2. Changes in battery capacity during field tests.

200 cycles, the vehicle could not travel the prescribed distance. During bench tests, capacities declined by about 20% for $C_3/3$ discharge and about 30% for $3C_3$ discharge. Thus, it is necessary to improve both the discharge characteristics and the cycle-life performance.

2.6. *Improvement of discharge characteristics*

At first, thick positive and negative plates were used to give deep-cycle service. The automobile manufacturers, however, requested batteries with greater specific power in order to improve the power performance of their vehicles. For this reason, batteries were designed with more and thinner plates. This raised the specific power from about 200 to 300 W kg^{-1}. As there will probably be demands for even greater specific power, attempts are being made to develop batteries with thin plates and long service life.

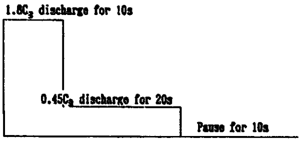


Fig. 3. Discharge pattern of JEVS (under development).

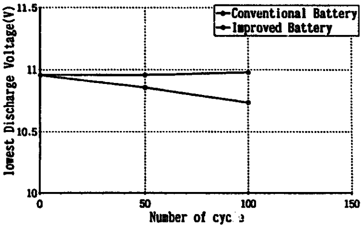


Fig. 4. Change of the lowest discharge voltage in bench tests.

2.7. *Improvement of cycle-life performance*

2.7.1. *Better negative plates*

Because a decline in negative-plate performance is observed in field tests, performance was improved by adopting a new plate composition. The cycle-life test was conducted with the JEVS method; the pattern illustrated in Fig. 3 was repeated 90 times. Under such service, the performance of the negative plate was clearly manifested. The results obtained after 100 cycles when changing the composition of negative active-material are given in Fig. 4. Using the conventional composition, the lowest discharge voltage gradually declines as the test proceeds, but with the improved composition there is hardly any drop in the lowest voltage. The $3C_3$ capacity test was also performed at the completion of each set of 50 cycles. After the 100th cycle, batteries with the conventional composition exhibited a capacity loss of about 10% of the initial capacity, but batteries with the improved composition suffered no capacity decrease at all. This demonstrates the effectiveness of the improvements made to the negative active-material.

2.7.2. *Better positive plates*

Typical results obtained in cycle-life testing while changing the composition of positive active-material are presented in Fig. 5. The test was conducted using 100% depth-of-discharge at the $C_3/3$ rate. This gives a good indication of positive active-material performance. With the conventional composition, the discharge time gradually shortens and batteries reach 80% of their rated capacity after about 150 cycles; thereby, service life is ended. By contrast, batteries with

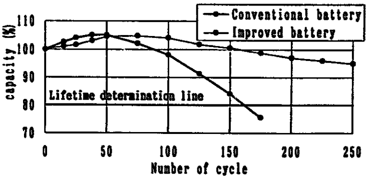


Fig. 5. Changes in battery capacity during bench tests (repeated discharge to 100% at $C_3/3$ rate).

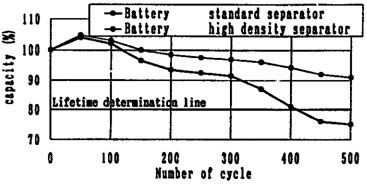


Fig. 6. Changes in capacity during bench tests (SBA method: repeated discharge to 80% of $C_3/3$ capacity).

improved positive plates experience an approximate 5% drop in the initial discharge time after 250 cycles. This shows the effectiveness of improving positive active-material.

2.7.3. *Better separators*

Separators play a major role in enhancing the cycle-life performance of batteries. The results obtained from changing the separator type are given in Fig. 6. The SBA test method was employed. This repeatedly discharges the battery to 80% of its rated capacity. Batteries with standard glass separators reached the end of service life after about 400 cycles. By contrast, batteries using glass separators that have high density and excel at maintaining compression on the plates still delivered good capacity after about 500 cycles.

3. HIMR bus batteries

A cutaway view of the HIMR bus developed by Hino Motors is shown in Fig. 7. The bus carries 25 batteries (65 Ah, $C_5/5$ rate) on the underside. The battery specifications are given in Table 4.

3.1. *Field test data*

The voltage and current characteristics experienced by the HIMR bus during field tests are given in Fig. 8. While driving, charging and discharging are intermittently subjected to a current of about $2C_3$. The total daily amount of discharge varies according to the route but, on average, it is about twice the rated capacity. Due to the intermittent discharges at large currents, the battery temperature rises to about 60 °C during the summer months.

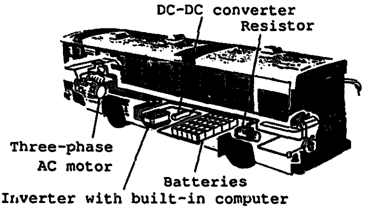


Fig. 7. Cutaway view of diesel–electric hybrid bus.

Table 4
Battery used in HIMR bus

Item	Specification
External dimensions	
Length (mm)	305
Width (mm)	171
Height (mm)	236
Weight (kg)	24
Voltage (V)	12
Capacity (Ah)	65

3.2. *Results of bench cycle-life tests*

We have continued to improve the batteries that are actually being used in the HIMR bus. These improvements are based both on the results of cycle-life testing that uses a pattern that simulates charging and discharging when used in vehicles (Fig. 9) and on the results of field cycle-life testing.

The results of bench tests are presented in Fig. 10. The following observations have been made.

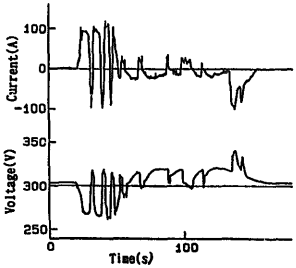


Fig. 8. Battery current and voltage characteristics during field tests.

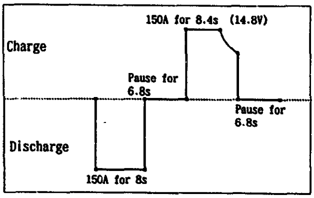


Fig. 9. Battery charge/discharge pattern during life-cycle tests.

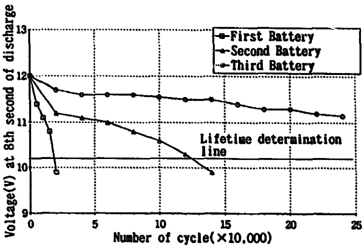


Fig. 10. Life-test results for HIMR bus batteries.

1. Bench tests for the first set of batteries indicate a service life of 20 000 cycles. Failure is due to the accumulation of $PbSO_4$ on the negative plates. This accumulation was especially large on the lower parts of the plates and, in some instances, was more than 40% of active material weight.
2. On changing the battery specifications by increasing the number of plates to improve negative plate charge acceptance, the life is extended to between 100 000 and 150 000 cycles.
3. Performing equalizing charges at appropriate periods also enhances the practical cycle-life performance.
4. In order to improve the charge acceptance of negative plates, the negative-plate composition has been changed in the batteries and the bench cycle-life test has passed 240 000 cycles, the batteries are still healthy.

Further changes are now being considered for the next battery design. These changes include increasing the number of plates.