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Charging strategies for valve-regulated lead/acid batteries in electric-vehicle applications

M. Fernández *, F. Trinidad

TUDOR Research Laboratory, Crta. N-II km 42 (Post Office No. 2), 19200 Azuqueca H. (Guadalajara), Spain

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Abstract

There is a widespread feeling that the electric vehicle must play an important role in the future, beginning with special applications in specific areas such as urban transportation and goods delivery, then spreading afterwards (in the medium- to long-term) to more complicated ones, like inter-urban use. From the point of view of the valve-regulated lead/acid battery, some problems remain to be solved before the technology can fulfil its task in any of the foreseen applications. This work concentrates on developing charging strategies to overcome the problem of limited vehicle range (typically 60 to 120 km). To increase the range, a straightforward solution from a practical point of view is to include in normal use as many rapid recharges as possible that are compatible with maintaining performance, especially cycle life. In order to test the influence of such rapid recharges on life, a study has been performed, to determine the influence of final charging voltages, initial current, and final equalization step. Results are encouraging and indicate a positive influence of rapid recharging on life, particularly for high initial currents ($1C$ to $2C$). Very high cycle lives of the order of 500–600 cycles at more than 80% DOD are obtained in bench tests. From these results, new tests have been started using recharge schedules of 1 h/10 h alternatively. The results confirm the previous ones: lives in the range of 600 cycles are obtained with no deleterious effects. Overcharge factors are low, resulting in extremely low water consumption. Other schedules including a higher number of rapid charges for each normal charge have also been considered. © 1997 Published by Elsevier Science S.A.

Keywords: Electric vehicles; Lead/acid batteries; Fast charging; Cycle lives

1. Introduction

Lead/acid batteries of the valve-regulated type (VRLA) are used at present for different applications. The most important of these applications are in UPS telecommunication systems, emergency and security alarms, etc. This type of battery is designed, specifically, to work under floating conditions, on permanent charge at very small overcharge voltages. In this application, cycling is not a special requirement because power failure is not a common situation, or its duration is, in general, low so that either sporadic or shallow discharges are imposed on the battery.

The situation and expectations with respect to VRLA battery applications are changing, because the intrinsic characteristics make VRLAs well suited for new uses that could not be sought in the past. This is especially true with respect to the cycling ability that has experienced a tremendous improvement in a relative short period of time [1]. The very encouraging values for cycle life are opening up new market opportunities for applications that range from light motive-power (sweeping machines, toys) to harder applications that require a higher degree of discharge. Among the latter, lies the use of these batteries for electric vehicles (EVs) in which the depth-of-discharge (DOD) is normally in the range of 60–80%, or even more.

EV applications imply new, very high, standards for the batteries [2,3]. In fact, a battery for EV use must have high specific energy, high specific power and, above all, the highest possible cycle life at very high DOD. High specific energy is needed to extend the driving range of the EV as much as possible. High specific power is necessary to preserve, during all the range of the EV, sufficient acceleration capability in order to be able to keep pace with normal traffic conditions. Finally, high cycle life is needed because in an EV the cost of the battery represents a high percentage of the total cost.

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* Corresponding author.

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In order to reach these best compromise between these conflicting properties of specific energy and cycle life, it is necessary to design the battery either to reach the best compromise between energy and life or to make the design to increase life as much as possible and improve the range of the vehicle in other ways. This latter approach is taken in this work.

2. Experimental

For the purpose of this study, VRLA batteries of the absorptive glass-microfibre (AGM) type were selected. The batteries were submitted to a very extensive and detailed cycling programme with the following objectives:

- to determine the real cycle-life capability of this technology under EV duty
- to study the influence of charging and discharging conditions on cycle life
- to look for alternative ways for improving the range, without sacrificing cycle life

The tests were performed in two types of VRLA batteries, both manufactured in the authors' company. The first one was a 12 V/60 Ah type, with L-3 format. The second one was a 6 V/180 Ah, or GOLF CAR, type. The L-3 unit is a standardized model of normal production for standby applications that has been redesigned to be accommodated to very deep cycling that is inherent in EV applications. The 6 V/180 Ah model is specifically designed for powering EVs, both passenger and delivery vans. This battery has been the subject of continuous development that finally resulted in a product almost optimized with respect to initial characteristics (specific power and energy) and life.

The main characteristics of both models are listed in Table 1 and the most important design details are given in Table 2.

The batteries, after previous characterization, were submitted to different discharge and charge conditions in order to test their possible influence on cycle life.

With respect to discharge, all the cycling was made according to the TC69 profile. In some cases, the degree of discharge was modified but the same discharge profile was always preserved for comparative purposes. The TC69 profile is composed of the following steps:

- 10 s discharge at $8I_5$ ($1.6C_5$) A
- 20 s discharge at $2I_5$ ($0.4C_5$) A
- 30 s rest

This sequence is repeated, until the battery voltage drops to 1.5 V per cell.

With respect to the main objective of this work, namely, the influence of charging conditions on cycle life, a different approach was adopted, i.e., to increase the charging rate as much as possible without adverse effect on cycle life. The following profiles were tested:

1. Influence of initial charging current; three different ranges were tested, viz., $2.0C$, $1C$ and $0.25C$.
2. Influence of charging voltages; three different levels of final voltages were used, viz., 2.45, 2.4 and 2.35 V per cell.
3. Influence of final equalizing charge: a final step of constant-current charge at low rate was used with the objective of: (i) adjusting the level of overcharge; (ii) raising the voltages of all the cells to eliminate any possible imbalance that can develop along the cycling. This charge was made at $0.033C_5$ for 2 h.
4. Influence of DOD on cycle life.
5. Low-rate and high-rate charges: in order to simulate the real situation in which the battery can receive some charge during the rest periods of the working time (breaks), a cycling schedule was employed with alternating low-rate ($0.25C_5$) and high-rate ($1C$) charges. If this scheme works well, it will be a very good way of extending the operating range (normal + high-rate refreshing charge) without affecting the final cycle life, because the design of the battery will be made to optimize the life.

Apart from the tests intended to determine the influence of operating conditions (charge/discharge) on cycling, another modification related to the design of the batteries

Table 1
Characteristics of test batteries

		L-3	GOLF CAR
Dimensions (L × W × H)	(mm)	278 × 175 × 190	245 × 190 × 275
Weight	(kg)	22.5	32.8
Voltage	(V)	12	6
Capacity	5 h rate (Ah)	62	180
	1 h rate (Ah)	54	135
Specific energy	5 h rate (Wh kg^{-1})	33	33
	1 h rate (Wh kg^{-1})	25	24
Specific power (at 20% SOC [a])	(W kg^{-1})	100	90
Cycle life (TC 69 profile)		500–700	500–700

[a] SOC = state-of-charge.

Table 2
Battery design criteria

	L-3	GOLF CAR
Alloys (positive/negative)	Pb–Ca–Sn	Pb–Ca–Sn
Grids	gravity cast	gravity cast
Number of plates (+/−)	4/5	7/8
Separator	glass microfibre	glass microfibre
Separator thickness (mm)	2.0	2.5
Container and lid	reinforced polypropylene	reinforced polypropylene
Safety valves	bunsen type	bunsen type
Charge	container formation	container formation

in order to increase life was evaluated. This modification affects the structure of the glass-microfibre separator and has been the subject of a patent (*Spanish Patent No. 0680105*) filed by TUDOR and introduced in various European countries. This modification has allowed a marked increase of the cycle life.

3. Results

3.1. Influence of initial charging current [4]

Three different groups of batteries were tested at the following currents: Group I: ~ C/4 (16 A); Group II: ~ C (50 A); Group III: ~ 2C (100 A). The same charging voltage (14.4 V) was used for all three groups and, in order to have approximately the same amount of overcharge, charging times were varied according to the value of the initial current. The regimes were: Group I: 16 A, 14.4 V, 16 h; Group II: 50 A, 14.4 V, 4 h; Group III: 100 A, 14.4 V, 2 h. The results are summarized in Figs. 1 and 2. Fig. 1 shows the C_5 capacity as a function of the number of cycles that the battery has supported. The capacity remains virtually constant during most of the cycling; it experiences a decline only when the battery reaches the end of life.

The initial current shows a marked difference in the sense that the higher the initial current, the higher the attainable life. For an initial current of 100 A, a life of around 600 cycles is reached, whereas for 50 and 16 A, the values are 400 and 200 cycles, respectively.

It is an important point to know the performance of the batteries in terms of the number of microcycles that are obtained in each of the cycles. This is because it gives a clear indication of the driving range that is achievable during battery life. As can be seen in the data given in Fig. 2, the number of microcycles experience a rapid decline from the very beginning of the service. This decline is more important in the batteries charged at the higher initial current (100 A), and this is due to the lower overcharge coefficient achieved with this charging regime. Lower levels of overcharge yield a higher decline in the number of microcycles, and vice versa. The group recharged at 16 A, 16 h with a high recharge coefficient exhibits less decline in microcycles than the group recharged at 100 A, 2 h, despite the fact that the total duration on cycling is shorter.

The overcharge coefficient on cycling follows the order 16 A, 16 h > 50 A, 4 h > 100 A, 2 h. Thus, it is directly

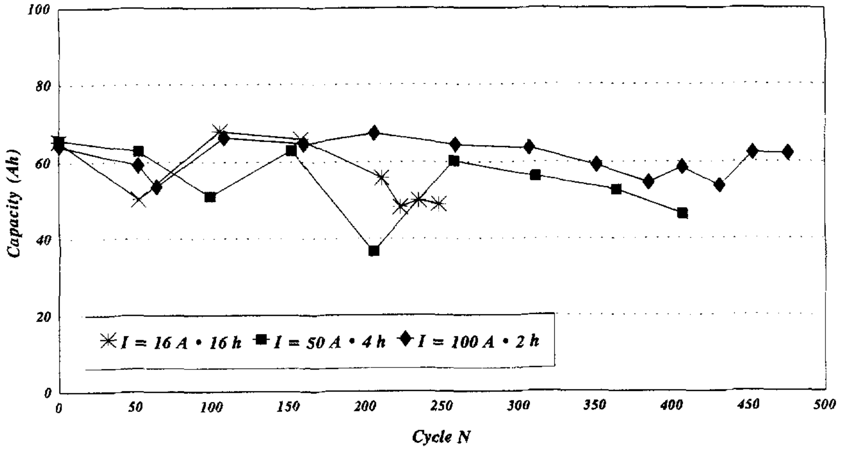

Fig. 1. Influence of initial charging current on C_5 capacity.

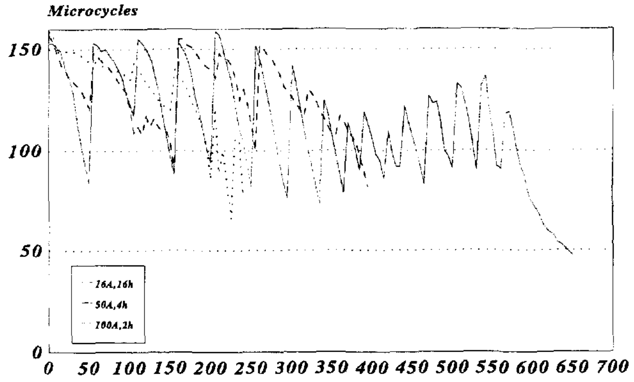

Fig. 2. Evolution of microcycles in TC69 discharge profile with cycling (Note recovery, after each life unit, 50 cycles.)

related to recharging time and is independent of the initial charging current at least for the recharging voltage of the test (i.e., 14.4 V). In order to achieve higher (i.e., more practical) coefficients other means such as increasing the final voltage or a final step at low constant current should be used to stabilize the performance of the batteries during cycling.

3.2. *Influence of final equalizing charge* [4]

Two groups of batteries were recharged with a final step at constant current, using continuous and pulsed current. The exact recharge profiles were: Group I: 50 A, 14.1 V, 4 h + 2 h, 1.2 A continuous current; Group II: 50 A, 14.1 V, 4 h + 2.4 h, 1.2 A pulsed current. The results are presented in Figs. 3 and 4.

The C_5 capacity remains almost constant during most of the cycling (Fig. 3). At the very end of life a decline is observed but there is no clear influence of continuous or pulsed final current. Similarly, the number of microcycles stays virtually the same and there is no net influence of either continuous or pulsed final current. The cause of such invariability lies in the fact that the overcharge coefficients are higher than in the previous test. Also, in the constant-current recharge period, the final voltage attained by the battery is of the order of 2.6 V/element (15.6 V/battery) and provides complete recharge and equalization of the battery.

The maintenance of the microcycles throughout battery life is a key feature because not only is important to achieve a long life, but also to assure a uniform performance of the batteries at all stages of their life. In this sense, it is necessary to use some means of equalization of the batteries, e.g., by increasing the charging voltage in IU charges, or working with IUI profiles as in the present case.

With respect to the overcharge coefficient, there is a slow and steady increase with cycling, starting from a value of 1.08 that is higher than in the previous test. With this profile, it is more easy to control the overcharge coefficient because most of it derives from the final current recharge step. For example, of the total 8% overcharge at the beginning, 6% comes from the final step, and only 2% from the constant-voltage recharge. Towards the end of life, overcharge amounts to around 15%, which is high taking into account its adverse effect on corrosion. In this way, perhaps it will be necessary to reduce the current of the final period, from the present value ($C/50$) to a lower one ($C/100$).

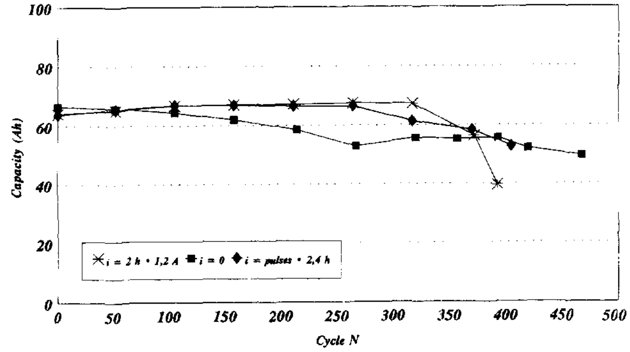

Fig. 3. Influence of final equalizing charge on C_5 capacity.

3.3. *Influence of charging voltage*

Three different groups of batteries were tested at three different charging voltages with the same discharge profile, in order to examine the influence of the final charging voltage on the life performance. The selected charging profiles were: (i) 50 A, 14.7 V (2.45 V/cell), 4 h; (ii) 50 A, 14.4 V (2.4 V/cell), 4 h; (iii) 50 A, 14.1 V (2.35 V/cell), 4 h. The results are summarized in Figs. 5 and 6. The C_5 capacity data (Fig. 5) show the best consistency, and the highest values are achieved with the highest charging voltage. Uniformity of results follows the order of the charging voltages. On the other hand, life is not so dependent on the charging voltage, because for both

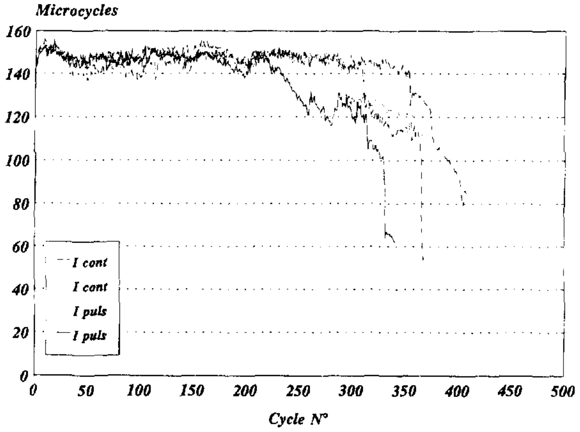

Fig. 4. Evolution of microcycles in TC69 discharge profile with cycling. (Note the constancy with respect to other tests.)

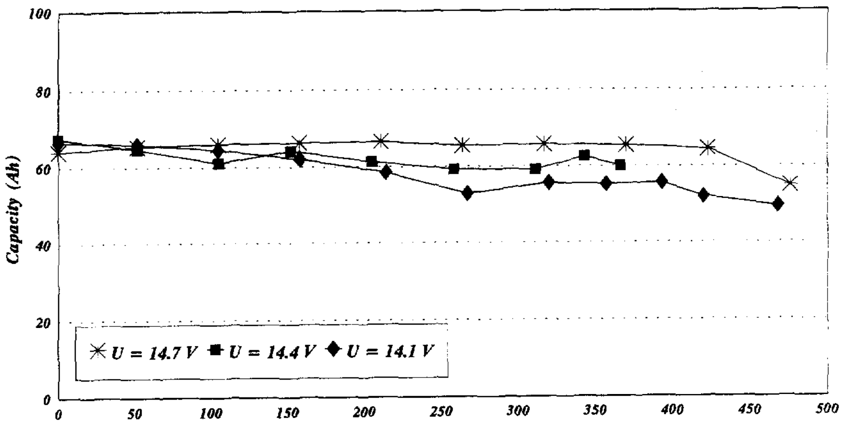

Fig. 5. Influence of charging voltage on C_5 capacity.

14.7 and 14.1 V, the total duration is the same, and for 14.4, the tendency is to reach the same duration, but is not achieved due to problems not related with the charging voltages (these batteries developed short-circuits at 400 cycles).

The number of microcycles from each unit is highly dependent on the charging voltage, and this is true from the very beginning of the test (Fig. 6). In fact whereas for 14.7 V the decline in the number of microcycles is relatively low, it increases for 14.4 V, and is the highest for 14.1 V.

The charging voltage also influences not only the variation of microcycles in each unit, but also the mean value of the microcycles obtained during cycling. It can be seen in Fig. 6 that the curves representing microcycles follow the same order as the charging voltages. This implies that the range is higher at higher voltages not only because of less variation but also because the higher absolute value of the microcycles.

Overcharge coefficients, as could be expected, are dependent on the charging voltages. The dependence increases as cycling proceeds. In fact, curves start from nearly the same point, but then diverge to reach values at the end of life of around 1.07, 1.10 and 1.15 for 14.1, 14.4 and 14.7 V charging voltages, respectively.

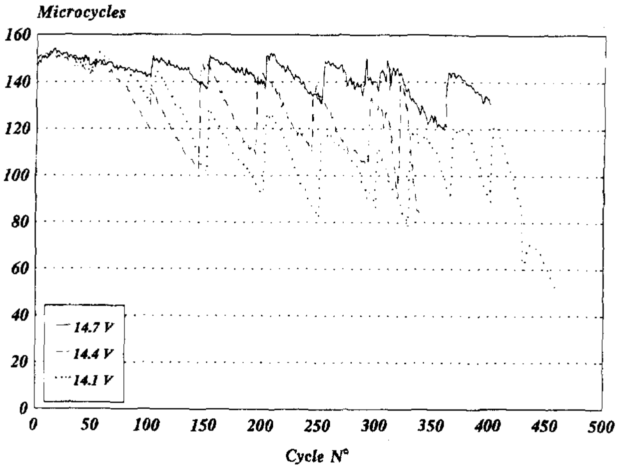

Fig. 6. Dependence of microcycles on charging voltage.

3.4. *Influence of depth-of-discharge* [6]

It is a well-known fact that the DOD is perhaps the most important parameter that determines battery life. It follows an almost exponential rule. This fact is well known and is established for both flooded and sealed batteries when cycled under constant-current discharge. This study aims to determine exactly the influence of DOD under discharge profiles used with discharge steps that are usual in EV service.

Four groups of batteries were tested, with DOD of 80% for groups I and II, and 50% for the other two. The exact conditions of the test concerning charge and discharge are given in Table 3.

In order to gain more information from the test, different charging conditions were selected within the groups with the same DOD. In one case, fast charge at an initial current of 1*C* was selected, whereas in the other a normal charge af $0.25C_5$ (16 A) was used, that is, the one normally available in the connecting points of the electrical network. The charging voltage was not the same in both cases, because in fast charge if it is not decreased slightly from 14.4 to 14.1 V, the temperature of the batteries, increases too much (reaching values of around 20 °C

Table 3
Test conditions

Group	Discharge profile	DOD (%)	Charge
I	TC 69	80	50 A, 14.1 V, 4 h + equalizing charge
II	TC 69	80	16 A, 14.4 V, 8 h + equalizing charge
III	TC 69	50	50 A, 14.1 V, 4 h + equalizing charge
IV	TC 69	50	16 A, 14.4 V, 8 h + equalizing charge

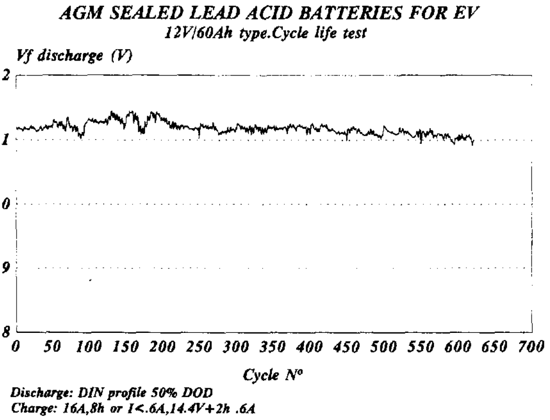

Fig. 7. Variation of final voltage on discharge with cycling, for charges at $I = 1C$ and 50% DOD. (Note smooth variation for both batteries.)

above the ambient temperature) and this could severely affect the expected life.

The results (Figs. 7–10) show that the groups with lower DOD display significantly better performance. The mean value for these groups is 1150 cycles, whereas it is around 500 cycles for the groups cycled with 80% DOD. Apart from the differences between both groups, it is more important to notice the very high cycle life that can be achieved with the recombination technology by virtue of its intrinsic characteristics. The values are near 1000 cycles for 50% DOD.

With respect to the possible influence of the charge profile, the results do not a show a clear trend. In fact, for the group cycled at 80% DOD, the sub-groups charged at 50 A, 4 h, gave a duration of 800 cycles, compared with 600 for the sub-group charged at 16 A, 8 h, but the durations were the same for both sub-groups cycled at 50% DOD.

3.5. *Low-rate / high-rate charges* [5]

The possibility of including between normal charges as many rapid recharges as possible is a very interesting possibility because it will be the most simple way of increasing the available range without making major changes to the design of the battery. This possibility is especially interesting for EVs for city duties for passenger use, because the total used time is reduced in general to two trips; the rest of the time the vehicle is at rest in the parking area, and in that time it can receive a fast or even a normal refreshing charge. The same is also true to a lesser extent for EVs used in a more intensive way such as delivery vans because there are always rest periods during the working time during which fast charges can be made. This case is more interesting because these applications require the range to be extended as much as possible.

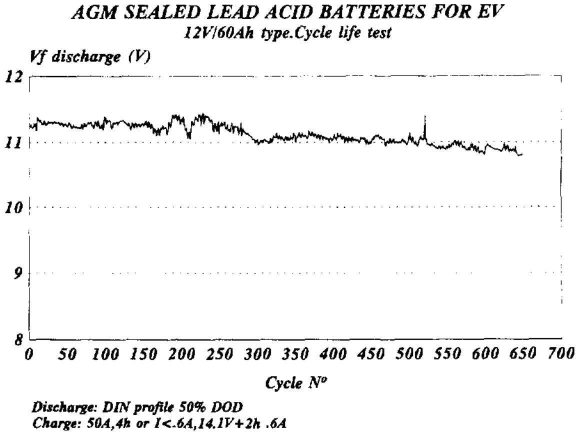

Fig. 8. Variation of final voltage on discharge with cycling, for charges at $I = C/4$ and 50% DOD.

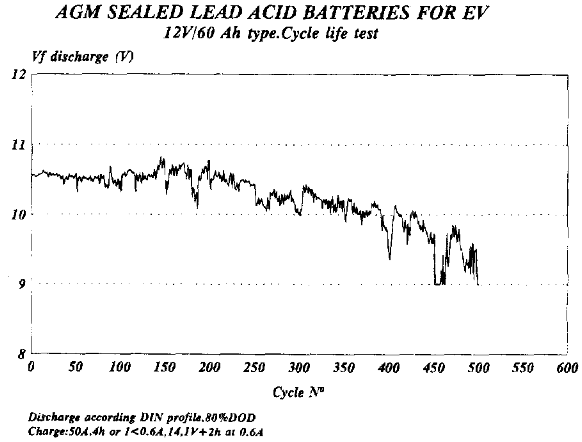

Fig. 9. Evolution of final voltage on cycling for charges at $I = 1C$ and 80% DOD.

In order to study this possibility, a series of tests were undertaken with batteries of rather a large size, namely 6 V/180 Ah of the Golf Car type. After initial characterization, the batteries were submitted to repetitive cycling, with discharge according to the TC69 profile, and using a charging profile of 1 h/10 h alternatively for odd and even cycles, for one group, and for the other 4 h at 7.05 V, with an initial current of $0.6C_5$ for comparative purposes. The

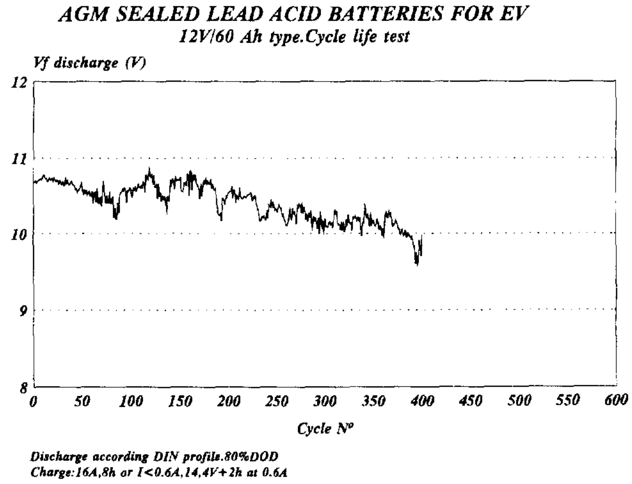

Fig. 10. Evolution of final voltage on cycling for charges with $I = C/4$ and 80% DOD. (Battery no. 3 developed short-circuit.)

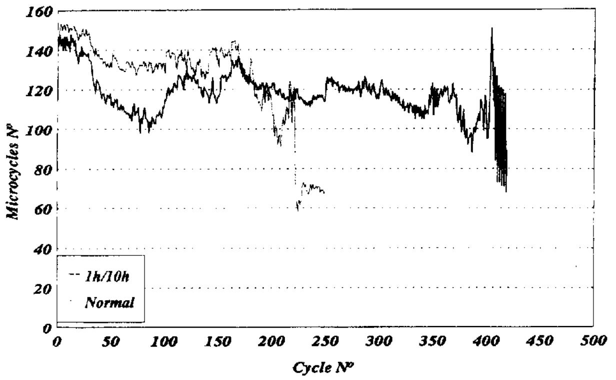

Fig. 11. Comparative performance of 6 V/180 Ah sealed batteries, cycled alternatively with standard and fast/slow charge profiles.

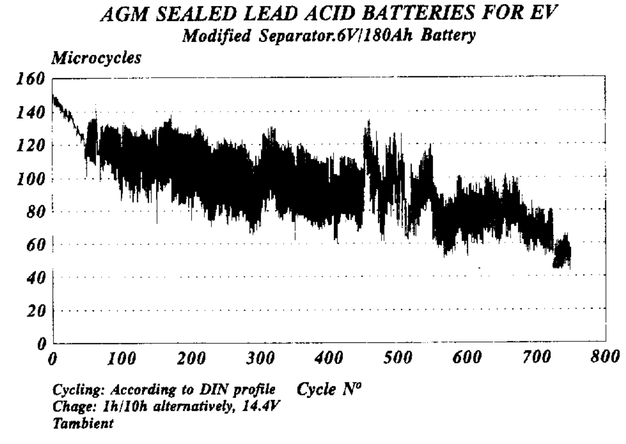

Fig. 13. Evolution of microcycles for 6 V/180 Ah sealed batteries, with the modified separator; charge profile 1 h/10 h.

results for both groups are given in Fig. 11. It is clear that for the fast/slow profile, the cycle life is higher; a fact that has been corroborated in further tests as will be shown later.

There are differences in performance concerning the number and constancy of microcycles. Whereas for the group charged with a 10 h profile, the number of microcycles varies in a smooth way, without sharp changes. For the group with 1 h/10 h charge, however, there is a broad variation on consecutive cycles, depending whether the previous charge has been fast or normal. When the previous charge has been a normal one, the number of microcycles decreases; after a fast charge, it increases. This apparently contradictory result is explained in terms of a temperature effect. After a fast charge, the battery warms up (the temperature increases by around 20°C above ambient) and in the following discharge more microcycles are obtained.

Concerning overcharge factor, in the case of 1 h/10 h charge profile, at the beginning > 90% of the previous discharge can be recovered at the 1 h rate. The necessary overcharge factor needed to sustain performance is achieved in the normal charge in which 115% of previous discharge is recovered. It gives a mean overcharge of 6% and this is sufficient to preserve the performance of the battery.

3.6. Components' modification

The traditional way of increasing cycle life, both in flooded and sealed batteries, has been to modify the properties of the plates, especially of the positives (increased thickness, higher density of the active material, etc.). In VRLA batteries, however, there is another component that plays a key role. This component is the glass-microfibre separator whose properties determine in a great measure the electrical performance of the battery. Because it is the intention to increase the battery cycle life as much as possible, attention is focused on the properties of this component that are important in this respect. Among the causes that can ultimately limit the battery life and are related to the separator performance, are the following: (i) short circuits across the separator; (ii) different degrees of acid saturation along the height of the separator, and (iii) development of acid stratification. These three items are

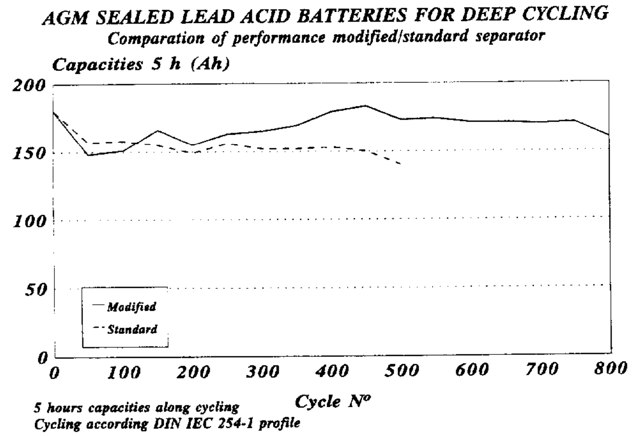

Fig. 12. Comparative results for cycling batteries with standard and modified glass-microfibre separators.

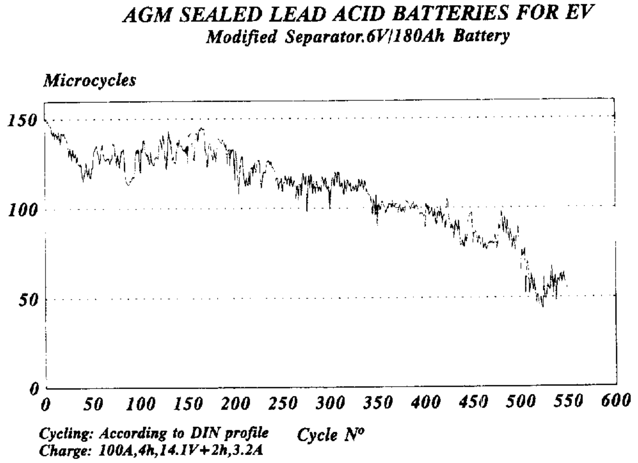

Fig. 14. Evolution of microcycles for 6 V/180 Ah sealed batteries, with modified glass-microfibre separator; normal charge.

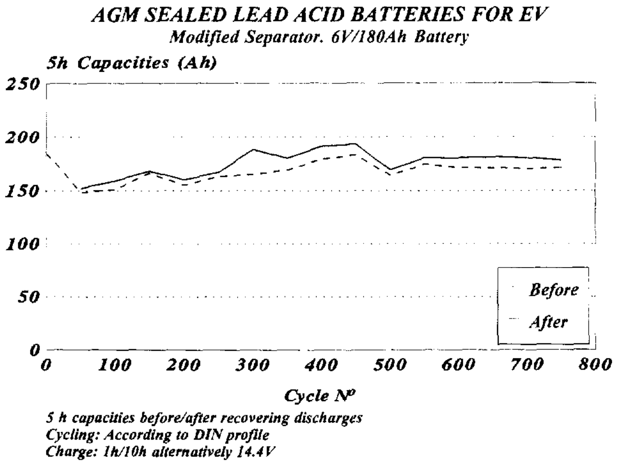

Fig. 15. C_5 capacities, before/after recovery discharges cycling; recovery discharges at C_{20} rate.

closely related to the internal structure of the separator and, more specifically, to the pore size [7,8]. In view of this, the internal structure of the separator was modified to decrease the pore size. Once the material had been prepared and tested, prototype batteries were assembled with the modified separator. The battery selected was the 6 V/180 Ah, Golf Car type that had already been tested. The prototypes were submitted to initial characterization (capacities), followed by cycle-life testing. As in the previous tests, the latter was performed under a TC69 discharge profile, and the charge for one group was a 1 h/10 h schedule, and a 4 h, $0.6C_5$ current with a final equalizing step for the other.

The results (Fig. 12), show a large improvement in cycle life (around 40%) with respect to the same battery with normal glass-microfibre separators. The microcycles obtained during life testing are shown in Figs. 13 and 14. It is clear that there is a broad variation in the group with 1 h/10 h charge, and a lower one for the other group. Comparison of the data for both groups also shows higher cycle life for the group with 1 h/10 h charge, which corroborates with the results of previous tests.

There is a slightly lower value of the overcharge factor for the group with 1 h/10 h charge (mean value). It starts at 103%, and ends at around 110%, but this is sufficient to sustain the performance, as the results show.

Periodic controls every 50 cycles included a measurement of the C_5 capacity, Fig. 15. There are two curves. The one at the bottom, represent the capacity at the end of each of the 50 cycles, without any preparation. In order to try to recover the lost performance of the battery, a method is used [9] that basically consists in making a complete discharge at low rate (i.e., C_{20} rate to a cut-off voltage of 1.5 V/cell) in order to force all the active material to work. After this recovering discharge, the C_5 test is repeated. The values are given in Fig. 15. It is clear that some recovery occurs, not only in the C_5 capacity evolution, but also in other parameters of the cycling (i.e., the number of microcycles tends to increase after these recovery discharges). The explanation for this performance seems to be related to the fact that whereas in normal cycling the real DOD is between 65–70% (which means that a significant amount of the active material remains idle), in the complete discharge, all the active material is forced to work, leaving it ready for the next series of cycling.

3.7. Weight loss

In all the cycling tests to date, an extremely low water loss has been observed, with values of the order of 0.25 g/cycle. This low value indicates that the recombination efficiency is very high, i.e., values above 98% are achieved. This value is about the same for all the charging schedules tested, and shows that is important to prepare batteries with high recombination efficiencies. In this way, different charging profiles can be used without the risk of drying out the battery electrolyte.

3.8. Internal resistance

The internal resistance was also monitored during all the cycling tests. The behaviour was similar for all the series tested. After an initial increase in the first 50 cycles, the resistance remains more or less constant during most of the cycling until the end of life is reached. At this point, there is a sharp increase.

4. Conclusions

1. A very high cycle life can be attained in VRLA batteries cycled under EV duties. Lives in the range 500–700 cycles have been demonstrated for DODs of 80%. When DOD decreased to around 50%, the life increases to around 1000 cycles.
2. Such high cycle lives, open the possibility of using VRLA batteries in applications requiring high cycle life, e.g., in EV services, for which is almost essential to have long cycle life because of the high cost of the battery. The values obtained implies a total duration in real use of between three to five years, depending on the battery operating conditions.
3. Another important conclusion is the positive influence of the fast charge on cycle life, as is demonstrated by the results achieved both in the batteries cycled with different initial charging currents, and with the 1 h/10 h profiles. This fact opens the possibility of using opportunity charges that, from a practical point of view, represent very important advantages.
4. It is clear that there exists the possibility of increasing the range of an EV by using charging strategies like the one tested (1 h/10 h alternatively), or similar. Because

there are not harmful effects on life, the range of the EV can be almost doubled by making use of opportunity charges.

5. Separator modifications can be very helpful in increasing cycle life, especially on taller batteries that are more prone to electrolyte stratification.

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