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The VRLA modular wound design for 42 V mild hybrid systems

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Abstract

Mild hybrid vehicles with 42 V electrical systems require advanced batteries with low cost, very high reliability and peak power performance. Valve-regulated lead-acid (VRLA) batteries could provide better performance/cost ratio than any other electrochemical couples, by improving their cycle life performance at partial state-of-charge (SoC), charge acceptance of the negative plate and thermal management under power assist conditions. Modular wound designs are being developed for this application, because they can combine the best attributes of the high power VRLA designs (low resistance and high compression) with a more efficient thermal management and could improve reliability by reducing the potential cell failures in manufacturing (better quality control could be assured for individual 3-cell modules than for complete 18-cell block batteries). Thermal management is an important issue for VRLA batteries in a power assist cycling profile. Although water cooling is very efficient, it is not economical and increases the weight of the complete storage system. The modular VRLA design allows air circulation around the external walls of every cell in order to maintain the temperature around 40 °C, even at very high power cycling profiles. In order to increase the life at higher depth-of-discharge (DoD) and consequently to optimise the weight of the complete battery systems, a new 6 V module has been designed with improved thermal management features. Cycle life performance under partial-SoC conditions (around 60% SoC) has been tested in both 6 and 12 V modules. The basic power assist profile as specified by the European car manufacturers is composed of a high power discharge (boost) period followed by a rest (cruise) and recharge in three steps (regenerative braking). Very good results have been obtained for 12 V VRLA spiral wound batteries under power assist profile (more than 200,000 cycles at 1.25% DoD, equivalent to 2500 times the nominal capacity), but smaller 6 V modules, although providing very promising results (50,000 power assist cycles at 2.5% DoD, equivalent to 1250 times the nominal capacity), still need further improvement to comply with the very demanding conditions of mild hybrid vehicles. Failure mode is related to negative active material sulfation, that could be overcome by improving charge acceptance with high surface conducting additives in the active material.

Keywords: Valve-regulated lead-acid; Spiral wound; 42 V systems; HEV specifications; Negative plate sulfation

1. Introduction

The specific requirements for a battery to be used in a mild hybrid system are not well defined, although it should be able to supply the power needed for at least the following functions:

- cranking of the internal combustion engine;
- power supply for auxiliary loads when the engine is stopped;
- boost the electrical generator for acceleration;
- recuperation of energy from regenerative braking;
- state-of-charge (SoC) management.

The high electrical power demand of mild hybrid vehicles is one of the main drivers for the introduction of 42 V systems; however, cost, reliability and performance of batteries will be one of the major challenges to achieve the targets of lower emission cost competitive vehicles. Although valve-regulated lead-acid (VRLA) batteries could provide better performance/cost ratio than any other electrochemical couples [1–3], due to their poor cycle life performance at partial-SoC, they have not been consider until very recently as an adequate storage system for this application [4].

VRLA battery cycle life performance can be improved by increasing the compression and positive active mass density, but charge acceptance is still insufficient for regenerative braking and thermal management is an important issue in some prismatic designs [5]. In order to achieve the high specific power and cycle life of new advanced batteries (such as lithium-ion or nickel-metal hydride), the spiral wound design is being considered as a serious candidate, because it can combine the best attributes of the high power VRLA designs (low resistance and high compression) with a more efficient thermal management. The basic manufacturing

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techniques for the large scale production of thin plates as well as the assembling procedures have been developed for 12 V modules that are already used for diesel engine starting and hybrid buses due to their high power and long life characteristics. In order to comply with the more demanding requirements of 42 V systems, the use of specially designed 6 V modules [6], with robust inter-cell connectors, that reduce the internal resistance and improve reliability has been proposed. These also have very high surface areas to allow external cooling, being that one of the most important features to increase cycle life under high power conditions.

Thermal management is very important to achieve the lifetime target and the special design of the modules with cooling channels around the cells will facilitate temperature control during regenerative braking. 36 V block batteries, although more economical to assemble, are not considered to be the best choice from the reliability point of view (potential failures will be exponentially increased with the number of cells and inter-cell connectors). On the other hand, 6 V modules can be assembled within the existing manufacturing lines for 12 V batteries, reducing the internal manufacturing scrap and the risk of cell failure during battery operation. Fig. 1 shows two possibilities for 6×6 V modular assembly, one with very low height that allows the battery to be placed below the passenger compartment and the other with a prismatic configuration that could be placed in the trunk or the engine compartment like present 12 V batteries. Other modular arrangements could be designed to place the battery assembly at different locations in the vehicle (under the seats, inside the spare wheel enclosure, etc.).

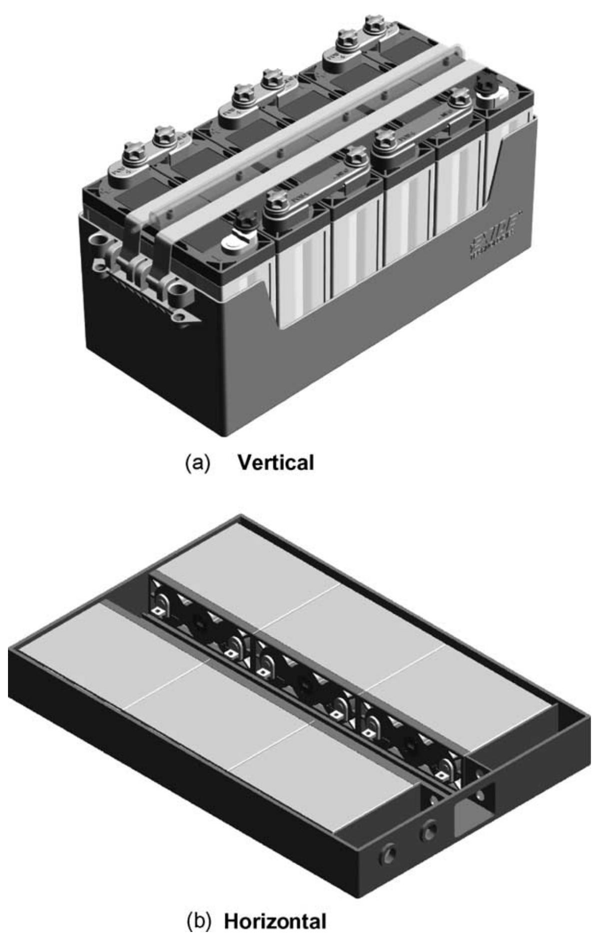


Fig. 1. 36 V valve-regulated lead-acid modular wound designs: (a) vertical; (b) horizontal.

2. Experimental

2.1. Battery assembly and general test procedure

Two different 36 V VRLA battery spiral wound designs based on a modular construction have been assembled and tested.

(a) 36 V 10 kW: Power optimised design, composed of 6×6 V modules with an internal construction of the cells that tries to maximise the power performance for the start–stop function.
(b) 36 V 15 kW: Cycle optimised design, composed of 3×12 V modules with more dense active material and higher compression of the separators in order improve cycle life under power assist conditions.

The purpose of the test procedure described below is to obtain reference data for the assembled batteries in order to understand the benefits and limitations of the modular VRLA design for 42 V mild hybrid systems. It is based on the requirements specified by European car manufacturers for hybrid electric vehicles [7]. In order to adapt these specifications to the particular 42 V electrical network, the international draft specification ISO/WD 21848 has been used to determine the voltage limits in charge (48 V) and discharge (30 V), except for cranking and high rate discharge tests, where a minimum voltage of 21 V is set. To ensure that each test is done with the battery in the same initial condition, a standard cycle, described below, should be performed before each test. The standard cycle is normally performed at room temperature. Other temperatures are specified in some special tests. The standard cycle (SC) is composed of a discharge phase followed by a charge phase as follows.

- Discharge (SDCH): Constant current at $0.5C$ to 30 V, C being the nominal capacity at the 2 h rate.
- Charge (SCH): Constant voltage 2.4 V per cell for 6 h, followed by a constant current phase at $0.03C$ for 4 h (105–110% overcharge).

2.2. Capacity determination at high rate discharge

One of the most important features of a 36 V VRLA battery is the ability to provide the needed power for the auxiliary systems when the engine is stopped. This test procedure tries to determine the capacity using different

Table 1
Test procedure to determine the capacity at high rate discharge

Step no.	Cycle	Temperature (°C)
1	Standard cycle	25 ± 2
2	Discharge $1C$ + SCH	25 ± 2
3	Discharge $2C$ + SCH	25 ± 2
4	Discharge $5C$ + SCH	25 ± 2
5	Discharge $10C$ + SCH	25 ± 2
6	Discharge $20C$ + SCH	25 ± 2
7	Discharge $25C$ + SCH	25 ± 2

constant current discharge rates. The capacity to a minimum voltage of 21 V is determined at different constant currents (from $1C$ up to $25C$) according to the test sequence specified in Table 1.

2.3. *Internal resistance, open circuit voltage and power determination*

In the same test the internal resistance (R_i), open circuit voltage (OCV) and constant voltage power (both in charge at 48 V and discharge at 30 V) with different SoC and temperature (0, 25 and 40 °C) will be determined following the test sequence specified in Table 2.

The above 10-step-sequence should be adjusted to draw 20% of SoC from the battery (the discharge time in step 8 is calculated accordingly) and will be repeated four times until the remaining capacity is 20%. The internal resistance is measured with an ac bridge (HP4338B) at a frequency of 1 kHz.

2.4. *Cold cranking*

The purpose of this test is to determine the cranking power (voltage: >21 V) and the minimum SoC that will allow to crank the engine at very low temperature. After a complete charge, the battery should be introduced into a chamber at −30 °C for a minimum of 16 h. The test is performed at a constant voltage of 21 V for a maximum time of 10 s and the SoC of the battery will be 100, 80, 60 and 40%. To reach the defined SoC, the $C/2$ current will be used adjusting the time accordingly (Table 3).

Table 2
Test procedure for OCV, R_i and power determination

Step	Procedure	Time
1	Internal resistance, OCV	Measurement
2	Discharge with $1C$ A	30 s
3	Pause	180 s
4	Charge with $1C$ A	30 s
5	Pause	180 s
6	Discharge @ 30 V	10 s
7	Pause	180 s
8	Discharge with $C/2$	Up to 0.2 C Ah
9	Charge @ 48 V	5 s
10	Pause	1 h

Table 3
Cold cranking test procedure

Step	Procedure	Time
1	Internal resistance, OCV	Measurement
2	Discharge @ 21 V	10 s
3	Pause	1 h
4	Discharge with $C/2$	Up to 0.2 C Ah
5	Discharge @ 21 V	10 s
6	Pause	1 h
7	Discharge with $C/2$	Up to 0.4 C Ah
8	Discharge @ 21 V	10 s
9	Pause	1 h
10	Discharge with $C/2$	Up to 0.6 C Ah
11	Discharge @ 21 V	10 s
12	Pause	1 h
13	Internal resistance, OCV	Measurement

2.5. *Power assist life cycle test*

The purpose of this test is to determine the evolution of capacity, voltage and internal resistance under partial-SoC cycling: C, U, $R_i = f$(battery age). With the proper thermal management (air flow: <150 m^3/h), the battery shall be discharged with $C/2$ to 60% SoC (0.8 h) and cycled according the "power assist profile" as indicated in Fig. 2, that includes the following steps.

Boost period	Discharge at 100 A for 18 s
Cruise period	Rest for 19 s
Regenerative braking	Charge at 90 A for 4 s Charge at 50 A for 8 s Charge at 20 A for 53–55 s
Stop phase	Rest for 18 s

In order to avoid overcharge, the maximum voltage during the charging period should be maintained but the charging time can be increased (in steps of 1 s) to avoid overdischarge. After every 10,000 cycles a standard cycle should be performed, followed by a complete charge (20 h at 2.4 V per cell + 4 h at $C/50$) and internal resistance determinations. The end-of-life is reached when both the maximum voltage in charge and the minimum voltage in the discharge are reached, it being not possible to recover the battery after a complete charge.

2.6. *Tear-down analysis*

After the cycle life test, a visual inspection of the internal components (grids, connections, active materials and separators) is performed. physical and chemical analysis of active materials were made as follows.

Positive active mass: BET surface area, pore size distribution (mercury intrusion) and chemical composition.

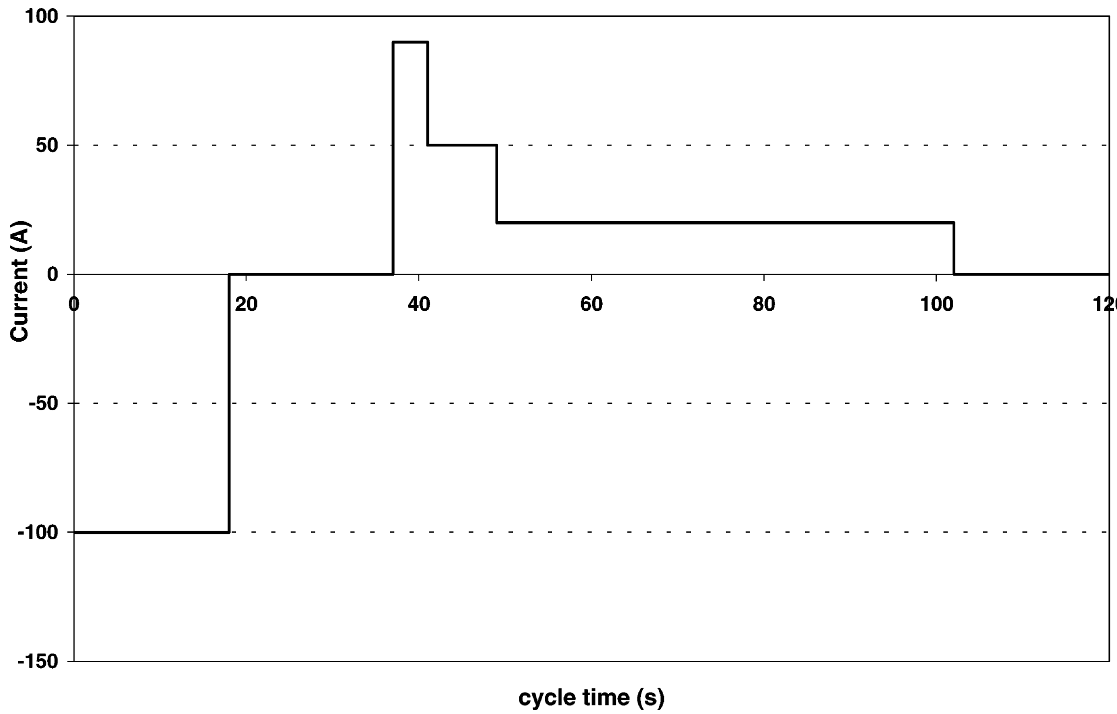


Fig. 2. Power assist profile for cycle life testing.

Negative active mass: BET surface area and chemical composition.

3. Results and discussion

3.1. Performance data

The specific requirements for a battery to be used in a 42 V system can be very different depending on the functions to be provided [8], but in general terms we can consider that the average power required will be 5–8 kW for cranking (down to −30 °C), about 10–15 kW for boost (up to 10 s) and regenerative power braking of 6–10 kW from the generator (up to 5 s). There is no specific requirement for low rate capacity, but there is the demand to supply the air conditioning and other auxiliaries during the stop periods that will consume about 2–4 kW (up to 2 min). Table 4 gives the performance data for the two 36 V modular wound batteries, being the values obtained inside the range of the power and energy demanded for a 42 V mild hybrid system.

3.2. Peukert equations

The high rate capacity of VRLA batteries follows an exponential law with the variation of current as can be seen in Fig. 3. As a consequence, the reserve of energy for every function to be supplied in the stop periods can be calculated through the corresponding Peukert equations:

$$I = 20.4 \times t^{-0.76} \quad (1)$$

$$I = 30.9 \times t^{-0.77} \quad (2)$$

where t is the time in ‘h’ and I is the current in ‘A’.

Very simple calculation allows us to determine the size of the battery needed for every specific high current demand. In particular, these two batteries will provide sufficient power for the air conditioning, electric steering or braking (up to 100 A) for a longer period than probably needed (6–10 min). Other lower consumption devices, like electric pumps, heaters, and so on (20–30 A) will take about 1 h to discharge the batteries selected completely. Under these assumptions, the 36 V battery needed for a 42 V system could be much

Table 4
Performance data for 36 V modular wound VRLA batteries

Battery prototype	36 V 10 kW	36 V 15 kW
Internal resistance (mΩ)	14	10
Volume (l)	13	22
Weight (kg)	25	48
Capacity (Ah)		
0.5*C*	21.0	34.6
1*C*	20.3	30.9
2*C*	17.6	26.3
5*C*	13.5	20.2
10*C*	10.5	16.3
20*C*	8.8	11.9
25*C*	7.0	10.7
Peak power at 25 °C (60% SoC)		
Discharge (kW)	10	14
Charge (kW)	5	8
Cold cranking at −30 °C (kW)	8	12

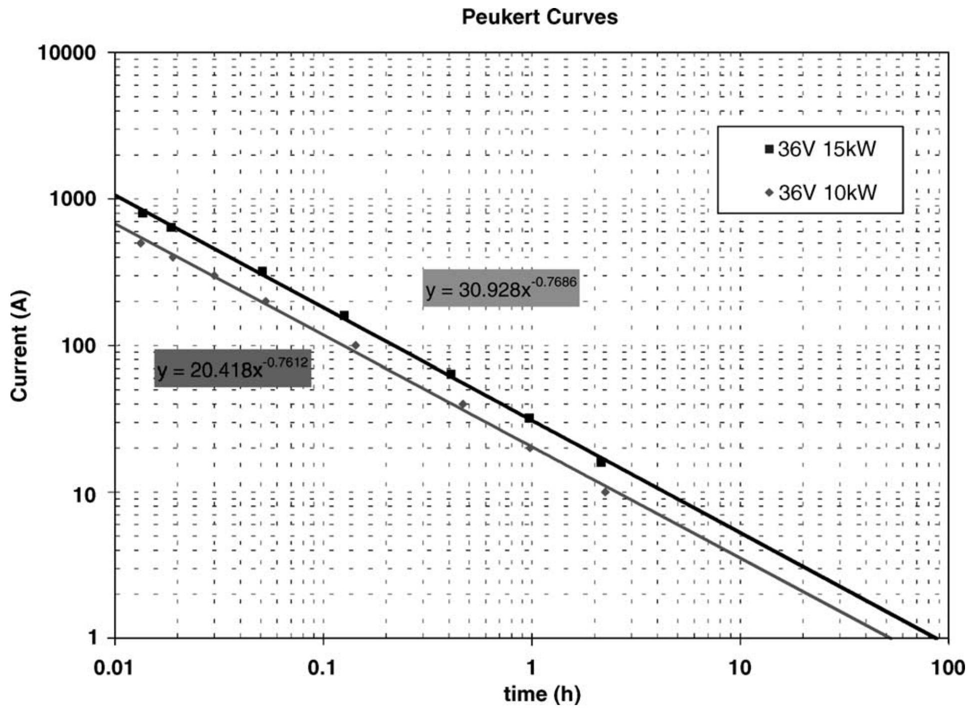


Fig. 3. Peukert curves of 36 V modular wound batteries: (a) 36 V 10 kW; (b) 36 V 15 kW.

smaller than previously foreseen. However, the most critical functions of a mild hybrid vehicle are the starting, boost and regenerative braking that require instantaneous power from a battery at a partial-SoC. Even reducing to a minimum the boost and regenerative braking functions (basic idle-stop system), the energy to be provided for all auxiliaries could discharge the battery in heavy traffic, compromising the starting function, especially if the car is stopped for rather long periods (airport test) and cranking needs to be made at low temperature.

3.3. Peak power and regenerative charge acceptance

One of the most important requirements for a battery to be used in mild hybrid vehicle is the peak power performance, both in charge and discharge, to be able to recover the braking energy as well as to provide acceleration boosting in the power assist mode. Fig. 4 shows the peak power and charge acceptance of the two batteries tested. Assuming that the power to be provided for boosting would be around 10–15 kW for a maximum period of 10 s, both VRLA batteries could efficiently provide the power to assist the engine by maintaining as high SoC as possible. However, the charge acceptance for regenerative braking (around 6 kW) could only be provided if the battery is maintained in a rather low SoC. For that reason, the battery should be maintained inside a narrow partial SoC (between 50 and 70%) to be able to comply with the two conflicting requirements.

The influence of temperature on the power performance can be seen in Fig. 5, where higher (40 °C) and lower (0 °C) ambient temperatures have been considered. Although, at low temperature the charge acceptance could be reduced considerably (<4 kW at 60% SoC), this should not be an issue due to the fact that under normal operation conditions, the battery would be heated up over the ambient temperature. In particular for power assist applications, a thermal management system should be introduced to control the battery temperature around 40 °C, and under these conditions, charge acceptance will increase over the specified SoC range (constant power values under 60% SoC showed in Fig. 5 are due to the limitation of the testing device).

Although the operation at low SoC seems more favourable under these conditions, from time to time, a complete battery charge should be performed in order to avoid the formation of irreversible sulphate in electrodes. Continuously operating at partial SoC may shorten battery life but frequent and excessive overcharges lead to drying out and thermal runaway. A battery management system with an accurate SoC indicator is required to optimise battery service life and to guarantee the restart of thermal engine whatever the conditions. Although this is not an obvious matter, there are indications from the battery performance data that allow us to determine the power ability from the internal resistance (R_i) and open circuit voltage (OCV). Fig. 6 shows the dependence of both parameters with the SoC. OCV varies linearly with the SoC, but the reference values will change throughout the life of the battery. On the other hand, R_i values show very small variations within the range normally considered (40–80% SoC), but will increase throughout the life. In order to asses the crank-ability of the battery system, an accurate measurement of the internal resistance should be included in the battery management system, due to the fact that no matter the origin

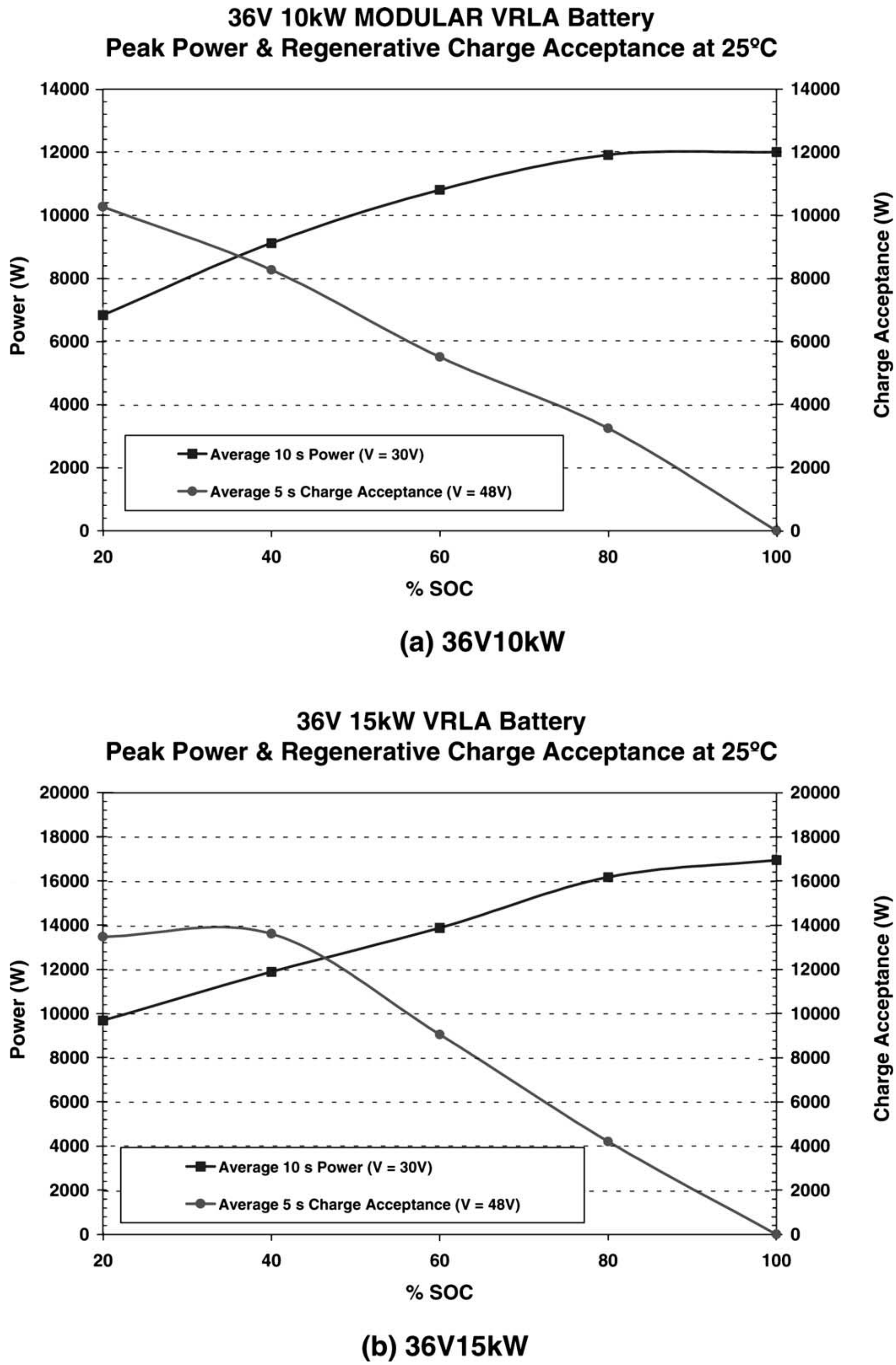


Fig. 4. Peak power and charge acceptance of modular VRLA batteries.

(low SoC or battery age), this value is directly related to the power in discharge of the battery and could determine the most critical function of the battery: the ability to crank the engine.

3.4. Cranking power performance

This is the most critical function of the battery system, because the combined effect of low temperature and SoC

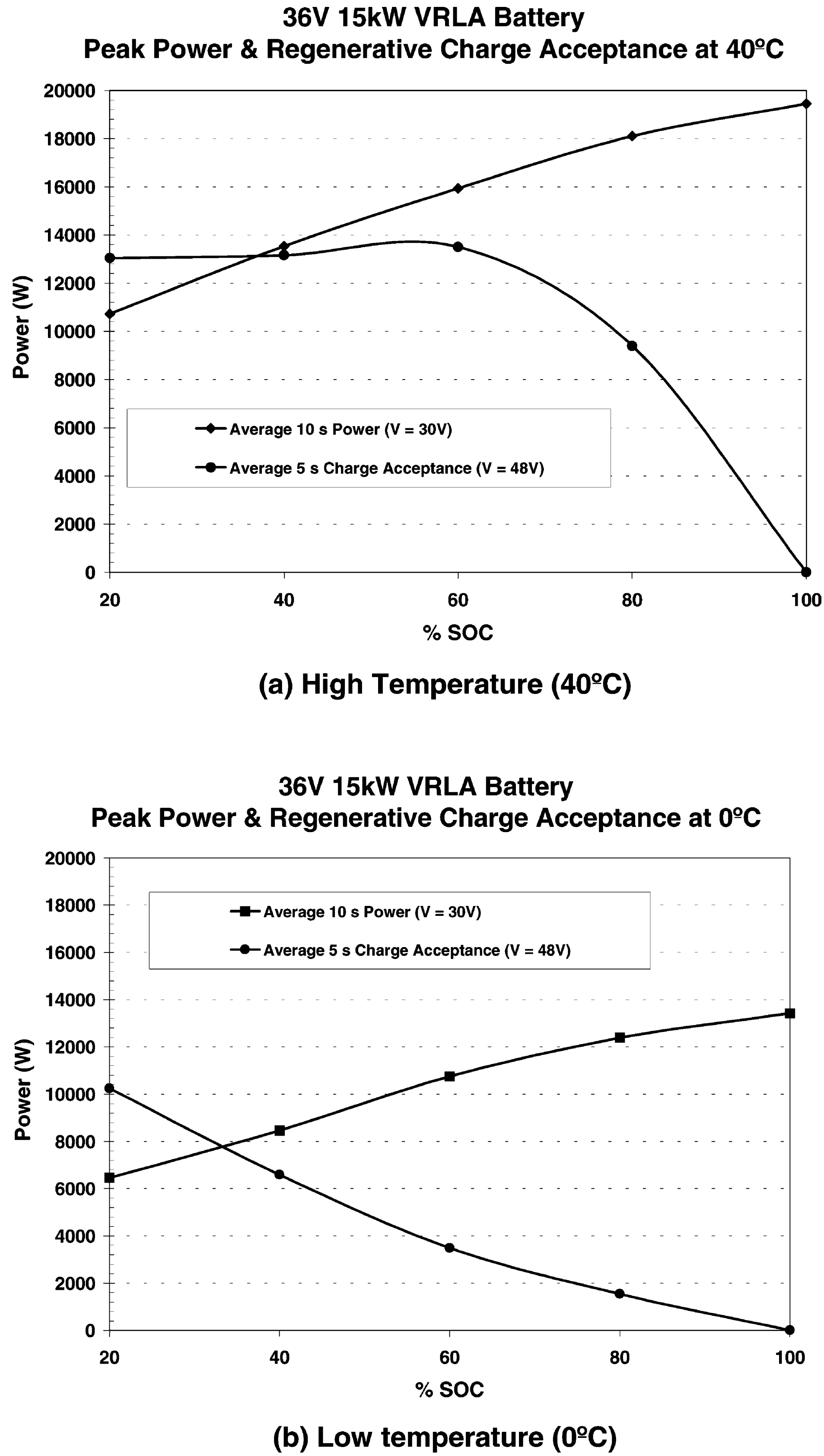
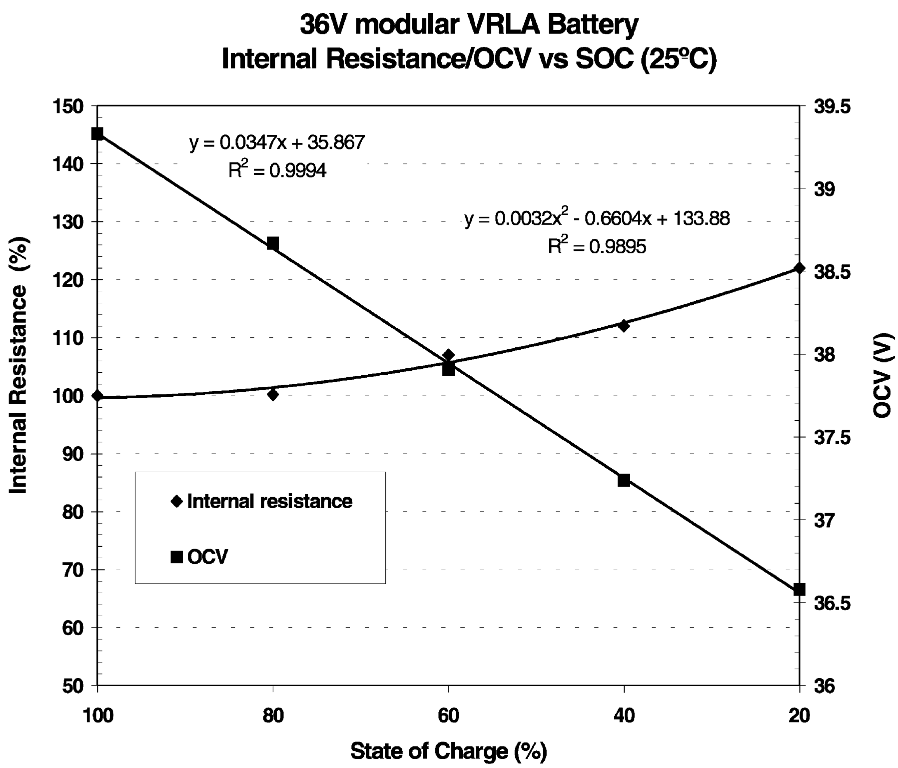
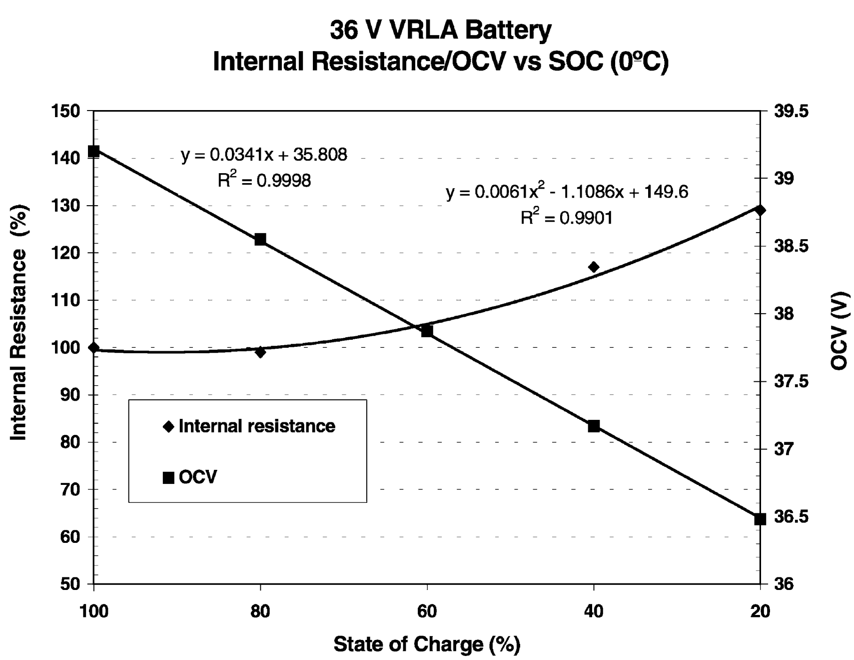


Fig. 5. Peak power and charge acceptance at different temperatures.



(a) Room temperature (25ºC)



(b) Low temperature (0ºC)

Fig. 6. Open circuit voltage and internal resistance.

could reduce the available power under the minimum required. Fig. 7 shows the influence of the SoC on the cranking power at very low temperature (−30 °C). After some driving in heavy traffic, the SoC could be reduced to a very low value (<60% SoC) and compromise the cold cranking in severe climate conditions (up to 8 kW at −30 °C could be demanded in extreme cases). In order to avoid cranking failures, a minimum reserve capacity should be assured by recharging

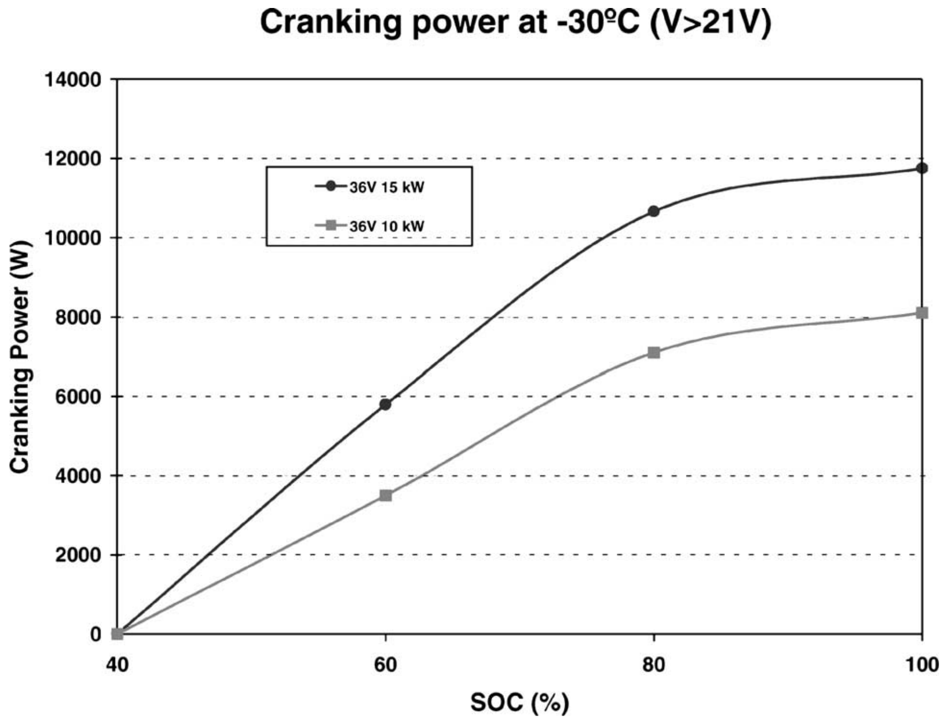


Fig. 7. Cold cranking power of modular VRLA batteries.

the battery completely when there is an excess of power from the generator (cruising at high speed in motorways) although at the expense of energy efficiency (high SoC reduces the regenerative charge acceptance). One possible solution could be to recharge the 36 V battery from the 12 V battery overnight (in a dual voltage architecture), although this will require a DC/DC converter in the electrical system. Another possibility is to disconnect some of the functions (boost or auxiliary loads) to recover the SoC of the battery before it falls below a certain limit. In all cases a certain margin between the minimum power required and the actual performance data will allow to us maintain the reliability of the cranking function in most cases. This drawback will be even more critical for other battery technologies (like Ni-MH) because power could be reduced more than an order of magnitude at very low ambient temperature and may require another power source (either another 36 V battery or capacitor) fully charged just for the starting function.

3.5. Life cycle determination

Cycle life performance under partial SoC conditions (around 60% SoC) is being tested in both 6 and 12 V modules. The basic power assist profile as specified by the European car manufacturers is composed of a high power discharge (boost) period followed by a rest (cruise) and recharge in three steps (regenerative braking). Fig. 8 shows the evolution of the 6 V module voltage and internal resistance throughout the power assist cycle life test. There is a tendency for the internal resistance to increase throughout life and is responsible for the continuously increasing voltage drop at the end-of-life. These data support the assumption of the internal resistance as one of the most accurate parameters to follow in order to determine the state-of-health of battery. Due to the high voltage on charge (>2.5 V per cell), some drying out is also taking place and this can contribute to the increase of the internal resistance throughout life.

Very good results have been obtained for the 12 V VRLA cycle optimised batteries (more than 200,000 cycles, equivalent to 2500 times the nominal capacity), however the cycle life for the smaller power optimised 6 V modules, although remarkable (50,000 cycles, roughly equivalent to 1250 times the nominal capacity), could be adequate for the start-stop function but still insufficient for a mild hybrid vehicle with boost and regenerative braking. One of the reasons is the higher depth-of-discharge (2.5% DoD versus 1.25% DoD) but also the lower charge acceptance of this rather small capacity battery. The implication, as remarked by Nelson [9], is that in order to assure longer life under partial-SoC, a heavier VRLA battery with more reserve capacity should be used for 42 V with power assist/regenerative braking function than would be necessary for a simple idle-stop system. As reported by Moseley [10], the useful capacity of VRLA batteries is strongly reduced under partial-SoC cycling. This effect is very critical for the small capacity 6 V module, but much less pronounced for the 12 V batteries (Fig. 9). Another interesting observation is that the full recharge performed every 10,000 cycles seems to be effective to recover the 12 V modules, but not at all for the smaller 6 V modules. Reduced charge acceptance of the latter due to the smaller surface area could be an explanation for this behaviour.

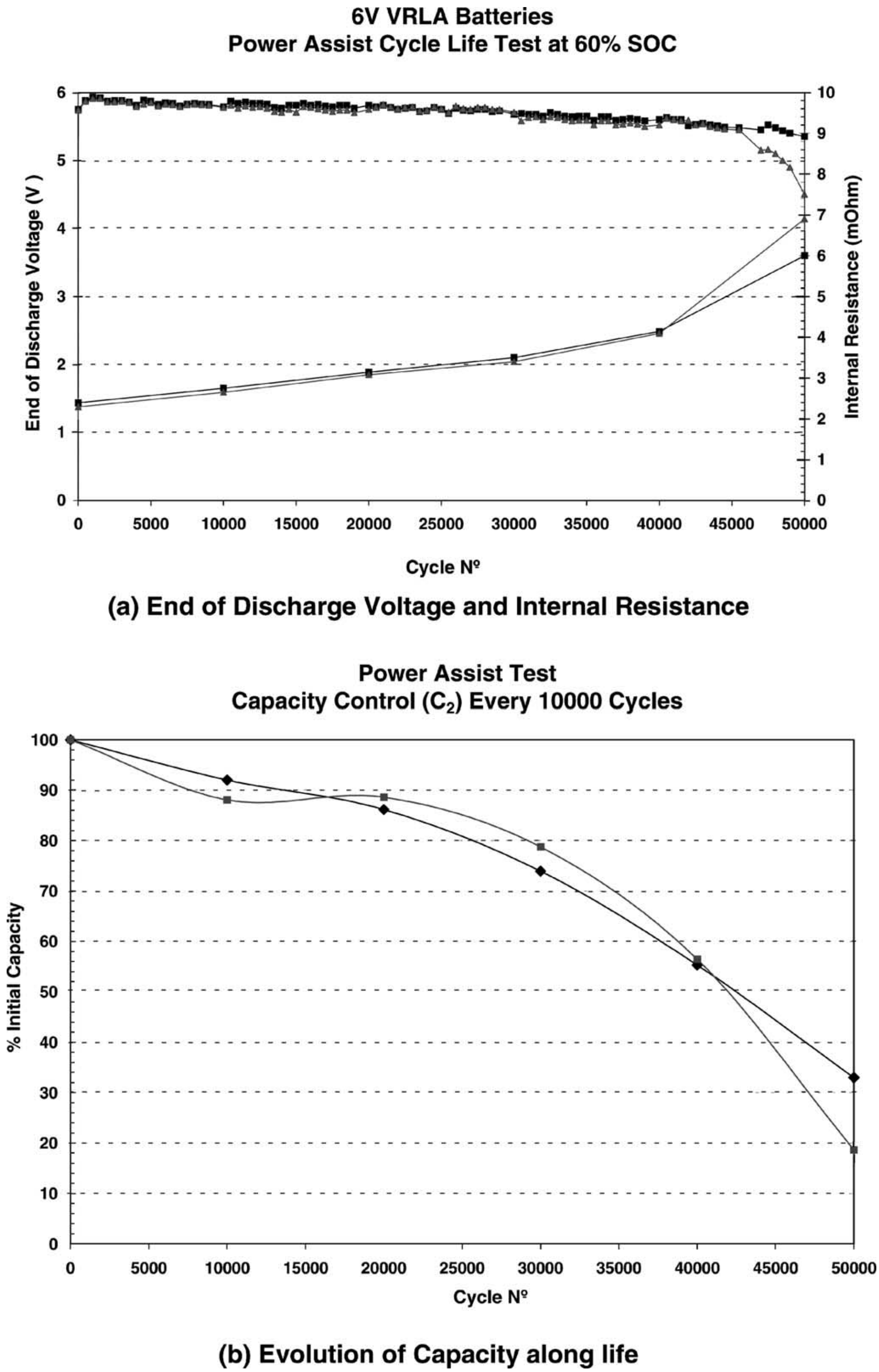
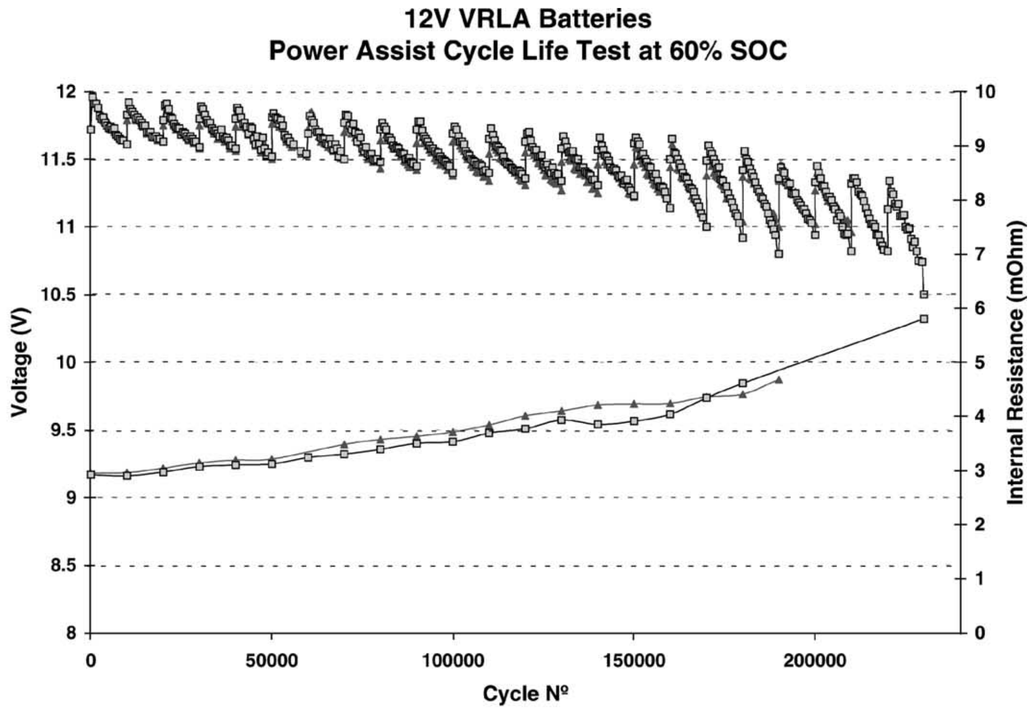


Fig. 8. Power assist cycle life of 6 V VRLA modules: (a) end-of-discharge voltage and internal resistance; (b) evolution of capacity.

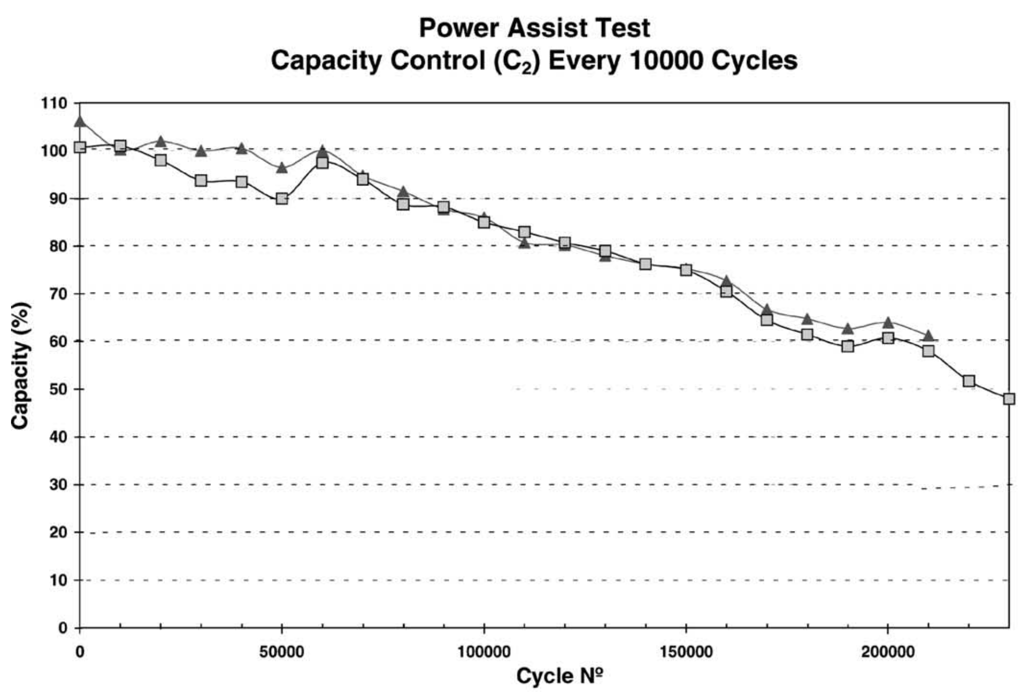
3.6. Analysis of active materials at the end-of-life

Once the modules completed the cycle life testing they were torn-down and the active material analysed with the results indicated in Tables 5 and 6.

Some of the plates showed a difference between the upper and lower part and, for that reason, separate samples from these areas were taken and analysed separately, the first value in the table corresponds to the upper zone and the second to the bottom area. The analytical data shows that the



(a) End of Discharge Voltage and Internal Resistance



(b) Evolution of Capacity

Fig. 9. Power assist cycle life of 12 V VRLA batteries.

positive plates are still healthy, although the upper zone has a more open structure than the bottom part of the plate, clearly indicating that the high current peaks are mainly supported by the area that is closer to the current collectors.

With regard to the negative plate, an accumulation of lead sulphate has been observed all over the plate, but mainly in the upper part that seems to be preferentially cycled at the very high current. No stratification effect has been observed

Table 5
Tear-down analysis of positive plates after the end-of-life

Battery type	Cycles fulfilled	PbO_2 (%)	$PbSO_4$ (%)	BET (m^2/g)	Porosity (%)	Pore size (μm)
6 V modules	Initial	89.8	1.5	4.82	53.9	0.45
	50000	96.1	0.2	2.48	56.6	0.88
		95.8	0.2	2.75	61.3	0.57
	50000	96.0	0.2	2.38	58.7	0.82
		95.4	0.76	2.5	60.9	0.50
12 V batteries	Initial	93.5	<0.2	2.7	46.1	0.78
		86.9	7.0	3.4	43.7	0.67
	210000	96.5	<0.2	0.90	54.5	1.4
	230000	95.0	<0.2	0.73	54.3	2.1

with regard to the position of the cells (vertical or horizontal) during the life tests.

The accumulation of lead sulphate in the bottom part in the initial stage is due to the lower formation efficiency, but at the end-of-life, there is more sulphate in the upper part of the plate. This observation is partially confirming the analysis made by CSIRO [11] that observed an accumulation of lead sulphate in the surface, but no difference has been reported along the height of the plates. One explanation to this apparently different behaviour could be the ohmic losses taking place in the bottom part of the relative taller plates of the 6 V modules tested (130 mm). In order to improve cycle life, it would be advisable to reduce the ohmic losses by improving the conductivity of the active mass. However, as important as conductivity is the active surface area of the negative electrodes by improving the effect of the expanders [2] and consequently to increase charge acceptance at the high current rates produced from the regenerative braking function. A combination of conducting additives (like graphite or carbon blacks) with high surface area expanders (both organics and inorganics) could be very effective to increase charge acceptance and reduce active material sulfation under power assist/regenerative braking conditions.

Table 6
Tear-down analysis of negative plates after the end-of-life

Battery type	Cycles fulfilled	PbO (%)	$PbSO_4$ (%)	BET (m^2/g)
6 V modules	Initial	2.0	2.0	0.63
		3.3	3.5	0.68
	50000	1.5	48.7	0.40
		2.8	20.7	0.55
	50000	1.8	31.4	0.50
		2.1	29.6	0.49
12 V batteries	Initial	3.9	3.3	0.84
		3.1	20.4	0.76
	210000	4.8	34.9	0.56
		3.9	30.8	0.59
	230000	2.5	45.7	0.45
		3.0	30.9	0.50

4. Conclusions

The VRLA modular wound design could provide a cost effective solution for 42 V mild hybrid applications and is specifically well suited to supply the high power needed for cold cranking and boosting the engine during the acceleration period. However, charge acceptance for regenerative braking is relatively limited at low temperature or high SoC. This drawback could be compensated by over-dimensioning the cell capacity at the expense of a heavier battery system, but still much less expensive than other advanced technologies (like Ni-MH or Li-ion).

A battery management system could be implemented by providing three main parameters of the battery: OCV that depends linearly on SoC, independently of temperature; internal resistance (R_i) that depends on temperature and state-of-health; and temperature (T). The combination of different algorithms to determine SoC (as a function of OCV and life), state-of-health (as a function of R_i and T) and power availability (as a function of R_i), will be a fundamental tool to assure the most critical function of the battery: crank the engine under the most demanding conditions.

Power assist cycle life exponentially depends on DoD (50,000 cycles at 2.5% DoD, but more than 200,000 at 1.25% DoD) and further improvement can be made by improving the cell design and the active material composition. The VRLA wound 6 V modules have been designed [12] to provide the maximum power both in charge and discharge, but also taking into account that thermal management is one of the most important issues for VRLA 36 V batteries in a power assist cycling profile. Although water cooling could be more efficient than air cooling, it is not economical and increases the weight of the complete storage system. The modular VRLA design allows air circulation around the external walls of every cell in order to maintain the temperature in the range of 30–40 °C, even at very high power cycling profiles (approximately 5C rate). In order to increase the charge acceptance of VRLA batteries, new types of additives to increase both conductivity and surface area would be one of the most important areas of future research, with a minimum target of 100,000 power assist cycles at 2–3% DoD (2000–3000 times the nominal capacity). The achievement of this target, while maintaining at the same time the low cost of the 42 V energy storage system, will make even more attractive a solution based on VRLA batteries than any other advanced electrochemical storage system.

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