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High power valve regulated lead-acid batteries for new vehicle requirements

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Abstract

The performance of high power VRLA ORBITAL™ batteries is presented. These batteries have been designed with isolated cylindrical cells, providing high reliability to the recombination process, while maintaining, at the same time, a very high compression (>80 kPa) over the life of the battery. Hence, the resulting VRLA modules combine a high rate capability with a very good cycle performance. Two different electrochemically active material compositions have been developed: high porosity and low porosity for starting and deep cycle applications, respectively (depending on the power demand and depth of discharge). Although, the initial performance of the starting version is higher, after a few cycles the active material of the deep cycle version is fully developed, and this achieves the same high rate capability. Both types are capable of supplying the necessary reliability for cranking at the lowest temperature (−40°C). Specific power of over 500 W/kg is achievable at a much lower cost than for nickel–metal hydride systems. Apart from the initial performance, an impressive behaviour of the cycling version has been found in deep cycle applications, due to the highly compressed and high density active material. When submitted to continuous discharge–charge cycles at 75% (IEC 896-2 specification) and 100% (BCI deep cycle) DoD, it has been found that the batteries are still healthy after more than 1000 and 700 cycles, respectively. However, it has been proven that the application of an IUi algorithm (up to 110% of overcharging) with a small constant current charging period at the end of the charge is absolutely necessary to achieve the above results. Without the final boosting period, the cycle life of the battery could be substantially shortened. The high specific power and reliability observed in the tests carried out, would allow ORBITAL™ batteries to comply with the more demanding requirements that are being introduced in conventional and future hybrid electric vehicles. However, some development in electrode thickness, separator and electrode corrosion must be made in order to match the performance of new advanced batteries (such as lithium-ion or nickel–metal hydride). Fortunately, the cost advantage of the VRLA technology over other electrochemical couples will continue to be a determinant for the future design of the electrical system of the new vehicles.

Keywords: Automotive batteries; Valve regulated lead-acid batteries; Cycle-life test; Absorptive glass mat; Fast charging; Hybrid electric vehicles

1. Introduction

During the next decade [1], it is expected that electric power demand for new vehicles will change drastically because:

- Vehicle electronic content will grow from 10 to 20%.
- The number of electric motors will be increased by 30%.
- Emissions, fuel economy, and safety standards are expected to become more restrictive.
- Weight reduction and improved engine efficiency will reduce fuel consumption by 10–15%.
- Electrically heated catalytic and start-up converters are expected to be required.
- Increased voltage systems are expected for at least 30% of the new vehicles.

Cost, reliability and performance of new battery technologies will be major challenges to be overcome before the new vehicle requirements are met. Among these new battery technologies, the most prominent are lithium-ion, nickel–metal hydride and high-power lead-acid sealed designs.

The conventional design of valve regulated lead-acid battery (VRLA) has a series of cells, each one containing a number of positive and negative electrodes connected in parallel and physically separated by a porous material which allows the free circulation of ions during the electrochemical charge and discharge reactions.

Due to the growing demands for increased power, battery designers have been obliged to increase the number of plates in each cell, and to decrease their thickness. This causes a reduction of the battery service life because corrosion of the thinner grids leads to earlier failure. As a consequence, batteries designed to supply increased starting current within the same physical size have a very limited cycle life, and usually fail prematurely. On the other hand, in batteries that

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are specifically designed to undergo deep discharge cycles, such as those used in traction electric vehicles, a lower number of plates are employed since they must have a higher thickness to allow a higher resistance to corrosion. As a consequence, these batteries are not able to provide the required high current performance necessary for engine starting.

The solution to these conflicting requirements is the modification of the basic design to one that has a large plate surface area which is independent of the number of plates, but still maintains the active materials under mechanical pressure in order to avoid expansion during the charge and discharge cycles.

There are three basic cell designs of VRLA battery that can accomplish the above mentioned solution, as shown in Fig. 1.

In the traditional design, based on prismatic cells, the physical dimensions of the cells impose a limit on the maximum effective area of the plates. The only way to increase the total surface area is to reduce the thickness of the plates in order to increase the number within the same volume. This leads to a tendencies for the active materials to expand during the charge/discharge cycles, and this tendency must be balanced by an increase of the internal pressure of the plate assemblies. Experience in battery manufacturing indicates that there is a limit to the internal pressure that can be achieved during the assembly; this limit is around 20 kPa. It is very difficult to maintain this pressure throughout the life of the battery due to the limited mechanical strength of the plastic materials of the battery containers (usually, polypropylene with a reinforcement additive).

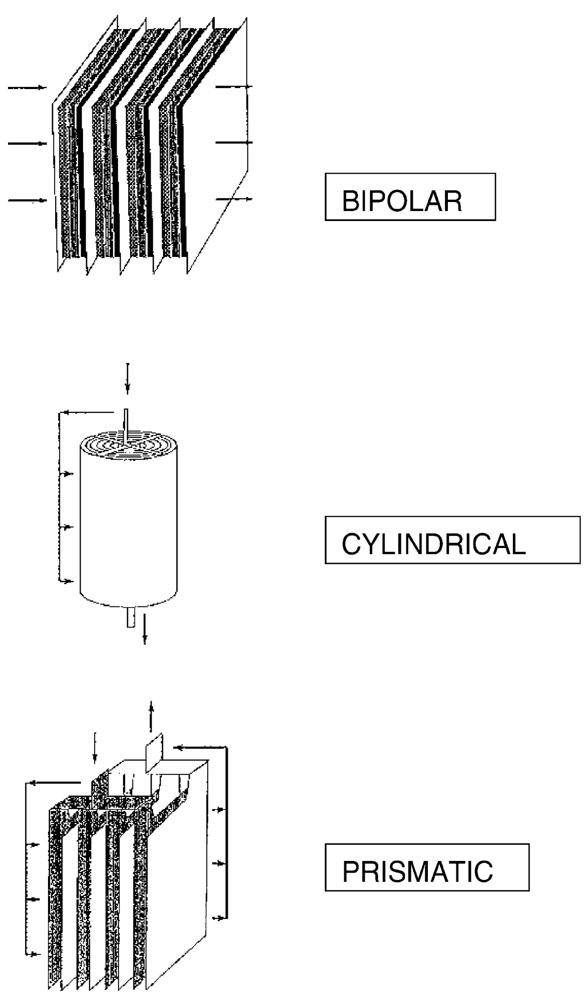


Fig. 1. Basic cell design of VRLA batteries.

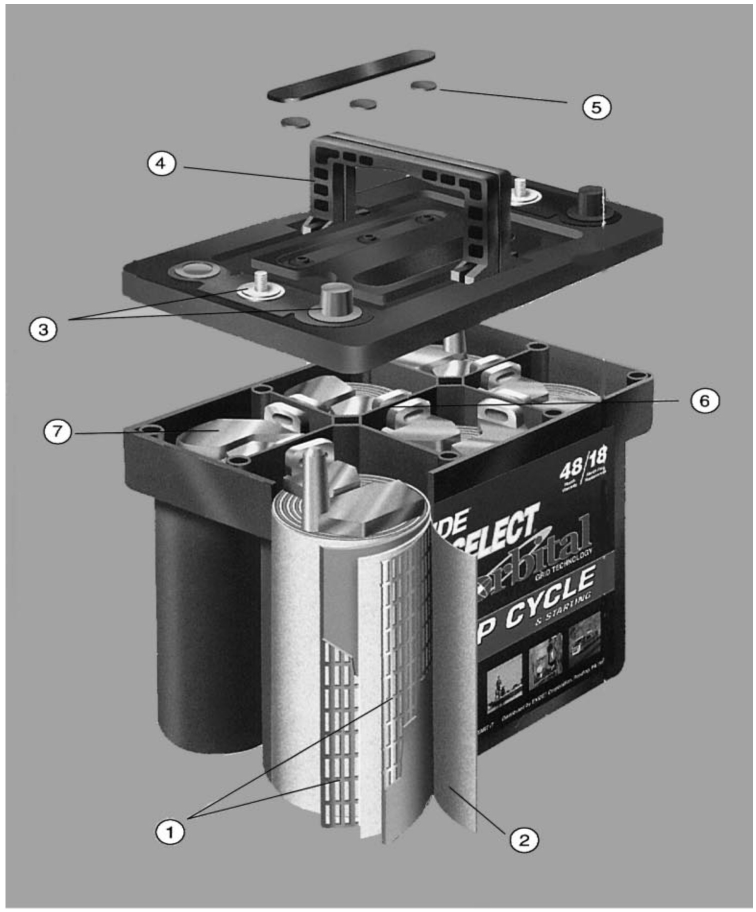
The cylindrical design is most widely used in the manufacturing of small primary and secondary cells for portable and electronic applications. In contrast to the traditional design, only the separator and the plate thickness limit the increase in the electrode surface. Also, the internal pressure of each cell is kept constant during the process because of the cylindrical geometry of the cells. In spite of its obvious advantages, it has not been the subject of much industrial development due to the complexity of manufacturing plates with a high surface area and minimal thickness.

The bipolar design allows increase of the surface area of the plates without increasing the number of connectors. The two faces in the bipolar plate design correspond to the positive and negative electrodes, respectively, in the traditional battery. In this case, however, they are physically joined through a conductor plate that acts as a current collector. In principle, there are a large number of metallic and non-metallic materials (conductive plastics) that could be used as a bipolar plate. Nevertheless, up to now, no materials have been found to resist the highly oxidising conditions that occur at the positive face. Generally, the plate is perforated by corrosion and, the battery fails due to short-circuits. New conductive materials that are being developed for other applications indicate that, at some time in the future, a solution will be found to this problem, but, in the medium term this design must be rejected for VRLA batteries due to the high risk of poisoning the electrolyte with impurities coming from the positive side.

2. High power valve regulated lead-acid modules

Recently, continuous manufacturing techniques for the large scale production of plates have been developed which, together with an automated assembly process, allow the objectives in costs and performance required to be achieved by a valve regulated battery. The individual cells include rather thin plates and polyester/glass mat separators [2] wound with a very high compression (>80 kPa) that can be easily maintained throughout life by using the cylindrical cell design. This design is increasingly being used in the manufacture of automotive batteries with high engine starting capacity and will be very suitable for the vehicles in development that demand higher power and reliability.

Fig. 2 shows a diagram of the arrangement of the cylindrical cells within a high power VRLA battery, which has been subjected to important improvements during the project



(1) Advanced Pb-Sn Technology Grids.

(2) Patented Glass Mat Separator.

(3) Two Sets of Terminals.

(4) Fold-away Handles.

(5) Six Valves "Isolated Cell" Design.

(6) Through-the-Partition Welding.

(7) Extra Heavy Duty Straps.

Fig. 2. High power VRLA Orbital battery.

development process. The most important features are the presence of cooling channels between cells and the use of one valve per cell. Every cylindrical cell body is thermally sealed to the lid, and electrically connected through the partition to the adjacent cell by means of an upper planar area below the lid [3]. In comparison to other designs [4], the inter-cell welding has been designed to be mechanically robust (increasing the vibration resistance) and to have a highly conductive cross section in order to overcome any heating of the connectors, which would otherwise be a problem due to high temperatures arising in the engine compartment. In addition to its higher reliability, the through the partition (TTP) system allows the isolated cell design, avoiding gas transfer from cell to cell and self-discharge due to thin films of electrolyte developed in direct bar connectors.

Other important features are related to the filling and formation processes used in the manufacturing. The inter-plate distance is rather short as required by the high power performance and compression of separators. As a consequence, filling becomes very difficult in the central part of the cell, producing hydration shorts and very fast self-discharge.

This problem degrades the reliability and reputation of very thin plate VRLA designs, in spite of their short-time high-rate discharge performance. A high vacuum filling process has been considered absolutely necessary, but not sufficient, to avoid the problem. Time is also another important variable, that represents a constraint in highly automated processes. The upper gas space [3], allows an acid reservoir that assists the whole formation process to avoid hydration shorts. On the other hand, pulsed current is applied to form the batteries, which are water cooled. The combination of external controlled cooling and internal temperature controlled pulsed charging avoids lead dissolution and stops the mechanism of hydration shorts.

3. High rate performance

3.1. Comparison with other VRLA technologies

All the design and process features previously mentioned have been developed with the goal to provide a battery that combines good cycling performance with a high rate capability. Fig. 3 shows a comparison with other battery technologies (flat or tubular plate gel versus spiral wound AGM design) that have been used for industrial applications due to their long life characteristics. For similar block dimensions, the low rate performance is very much the same, but at medium rate flat or spiral wound plates have much better performance than tubular plates. At very high rate (more than 2 C or discharge shorter than 0.3 h) the spiral wound design is better than the flat or tubular ones.

The coefficients of the Peukert equation ($I^n t = k$), clearly show the advantage of the spiral wound design over the flat or tubular plate designs. The closer the exponent of the current (n) to unity, the higher is the power capability; on the other hand, the higher the constant (k), the better is the low rate performance. As a consequence, the spiral wound design should be preferred for high power (starting, hybrid vehicle), while the flat plate is preferred for medium rate (electric vehicle, semi-traction) and the tubular plate is preferred for low rate applications (solar photovoltaic, traction). In principle, deep cycle life could be the main disadvantage of thin plate designs; however, as will be seen in the corresponding section, the high compression of the spiral wound design compensates the natural tendency of high power batteries to fail prematurely in deep cycle applications.

3.2. Cold cranking performance

Due to its high power capability, one of the most obvious applications is engine starting. A 12 V 50 A h module is able to provide up to 1000 A for more than 30 s with a voltage higher than 2/3 of the open circuit voltage (USABC and EUCAR requirement). This represents a discharge at 20 C, difficult to be sustained by other advanced batteries, such as lithium-based systems. Besides, the lower the ambient temperature, the higher the difference in favour of the VRLA

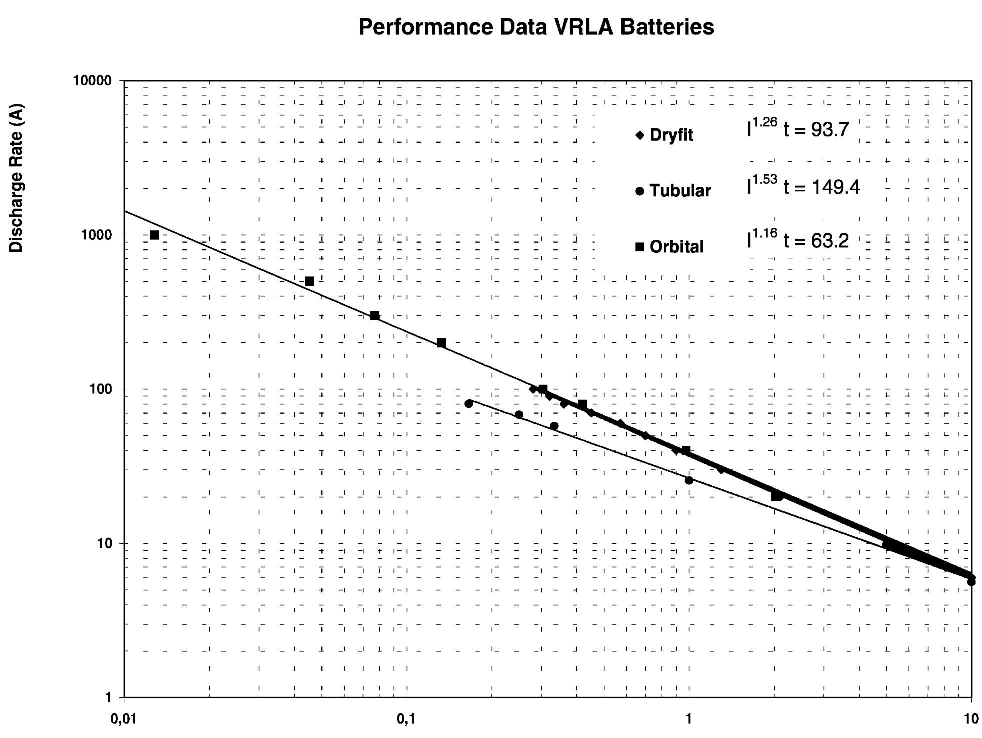


Fig. 3. Peukert graphs of VRLA batteries.

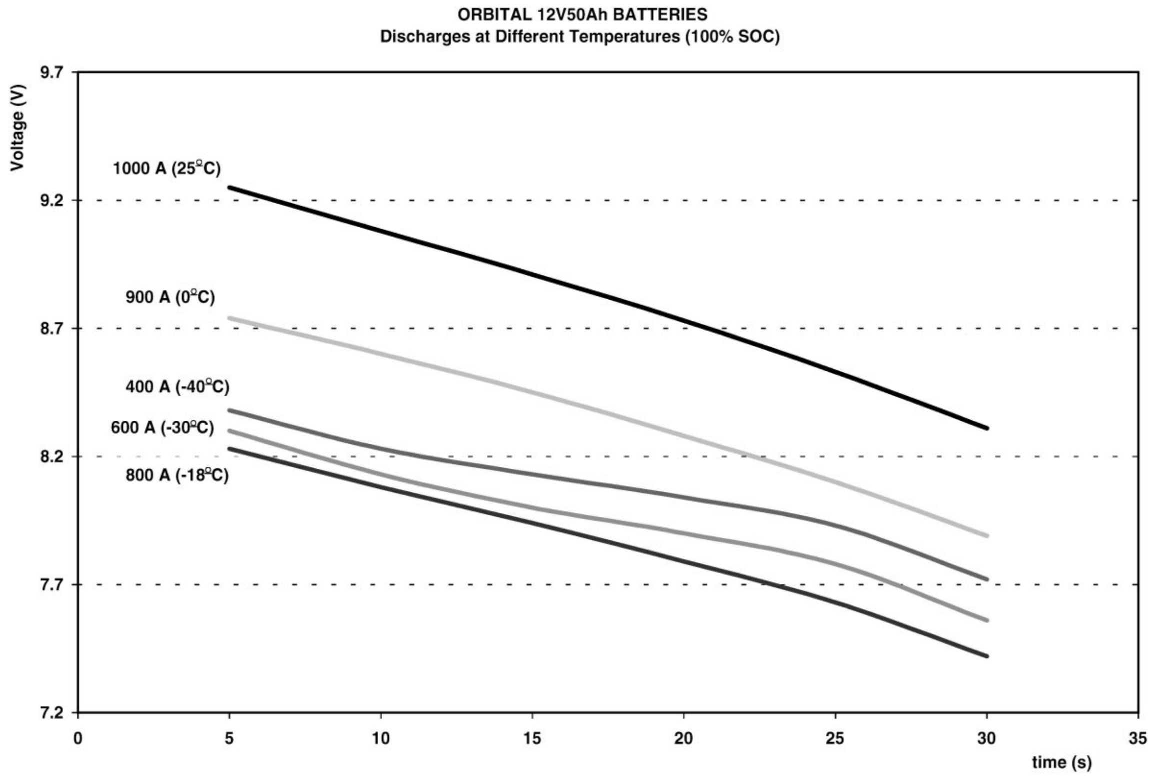


Fig. 4. Discharge curves of VRLA modules at different temperatures.

systems, due to poor low temperature behaviour of batteries with organic electrolytes.

Cold cranking performance is one of the most important requirements of today's vehicles. Fig. 4 shows that the spiral wound design is perfectly adapted for such a requirement and will be able to start the engine in any environmental conditions (down to −40°C).

3.3. Specific power

There are two different electrochemically active material compositions within the same basic cell design, depending on the power demand and the depth of discharge:

1. High porosity active mass for the starting application.
2. Low porosity active mass for the deep cycle requirements.

Even though the initial performance of the starting version is higher, after some cycles, the active material of the deep cycle version becomes fully developed and achieves the same high rate capability profile as the starting version.

The high power performance of both types is able to provide the necessary reliability for cranking even at the lowest temperatures. However, the starting type is lighter and thus the specific power achieved is significantly higher. Fig. 5 shows the cranking performance of both designs at different temperatures (from −40 to +40°C). A specific power of over 500 W/kg is achievable, similar to those of other advanced battery systems (such as nickel–metal hydride) at much lower cost.

New vehicle requirements for high power systems (42 V networks) fit very well with the high power capability demonstrated by the spirally wound design. In order to achieve the system voltage requirements for the new vehicles, several blocks must be connected in series. The non-spillable feature enables the battery to be mounted to give front access to the connections, if necessary, and provides for thermal management by installing air cooling fans below the base of every block.

4. Endurance tests

The high power capability of the Orbital batteries has not been achieved by disregarding other important requirements such as cycle life and reliability. In order to assess the high cycling endurance expected, high power VRLA batteries were tested according to different cycling procedures specified by the car manufacturers.

4.1. Shallow cycling at partial state of charge

Two orbital 12 V 50 A h batteries, one for starting applications and one for cycling applications, were introduced into a chamber at 25°C (±2°C) to be continuously cycled as

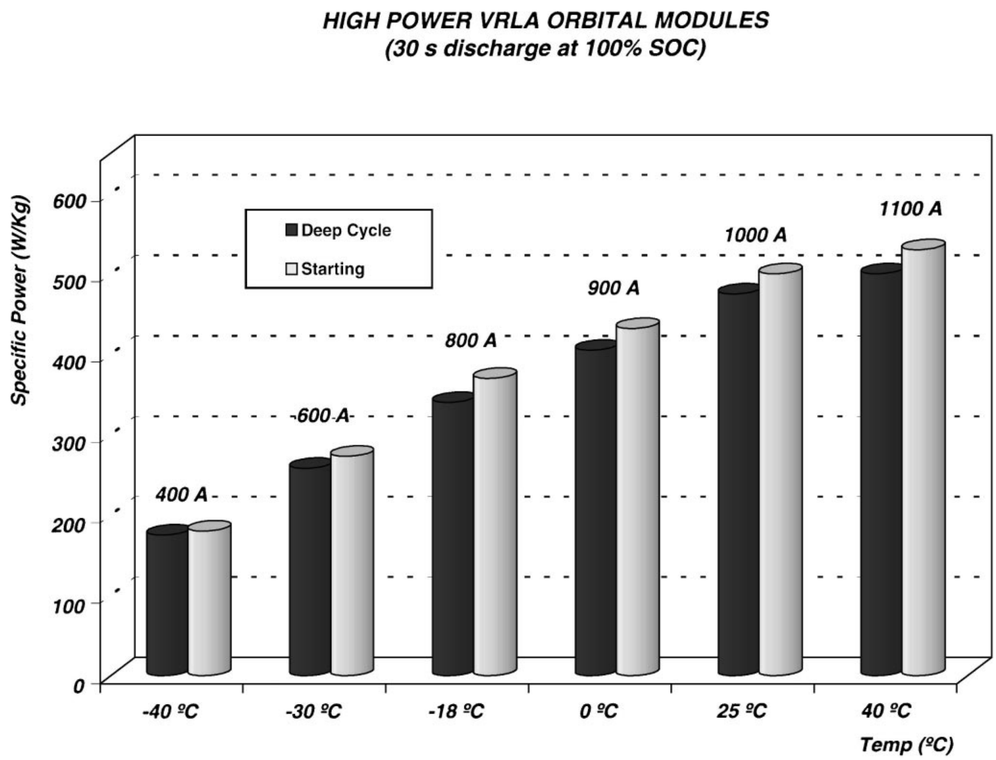


Fig. 5. Specific power of VRLA modules at different temperatures.

follows:

1. Discharge 2.5 h at 10 A (minimum voltage 10 V).
2. Cycle 85 times by discharging 30 min at 17.5 A (minimum voltage 10 V) and charging 40 min at 14.4 V (maximum current 17.5 A).
3. Discharge at 2.5 A up to 10.5 V.
4. Recharge 18 h at 14.4 V (maximum current 5 A).
5. Capacity test at 2.5 A up to 10.5 V.
6. Recharge 23 h at 14.4 V (maximum current 5 A).
7. Repeat steps (1)–(6) six times.
8. Cold cranking test for 30 s at 480 A/−18°C (minimum voltage 7.2 V).

Both batteries passed the test and the above procedure was repeated until failure. Fig. 6 shows the evolution of the capacity test with the number of cycles. After 1600 cycles at partial state of charge (more than three times the requirement), the starting type retained more than 60% of the initial capacity and the cycling type was still above the nominal capacity. The cycle life endurance in this test is well above any standard flooded battery used in today's cars.

4.2. Heavy duty cycle life test

Two Orbital 12 V 50 A h batteries (one for starting and another one for cycling applications) were introduced into a water bath at 40 ± 2°C and cycled 120 times as follows:

1. Discharge 2 h at 12.5 A (minimum voltage 10 V).
2. Charge 5 h at 14.4 V (maximum current 12.5 A).

After a 72 h rest period, a cold cranking test at 480 A/−18°C was performed (minimum voltage after 30 s should be 7.2 V). Both batteries passed the test and cycling was continued until failure. The Orbital starting type failed after 140 cycles (see Fig. 7). Teardown analysis after failure showed soft positive paste due to the high porosity of the active mass.

The Orbital deep cycle is still healthy after more than 600 cycles (five times the requirement). The low porosity of the active mass, together with the high compression design, gave this impressive result for a high power/thin plate valve-regulated design.

The test is based on the DIN standard, which means that both batteries can be classified as "heavy duty" for industrial vehicles, although the deep cycle design exceeded the requirement by more than five times.

4.3. Endurance at high temperature

The high temperature in the engine compartment of modern vehicles is reducing the life of conventional flooded batteries, especially in hot climates. VRLA batteries can be a solution to this problem, due to fact that recombination of gases reduces water loss. There is a high temperature test (75°C), based on the SAE J240 standard, that is being required recently by most car manufacturers (Fig. 8). In order to assess the behaviour of VRLA designs, two orbital batteries were introduced into a water bath at 75 ± 2°C and tested as follows:

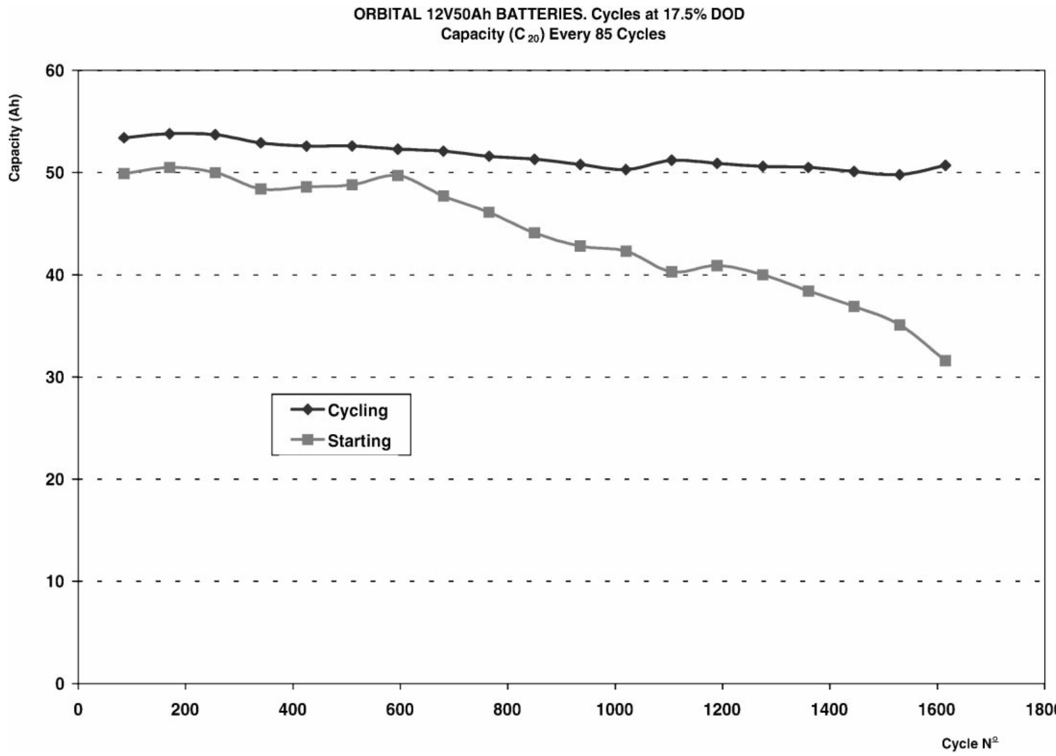


Fig. 6. Cycle life test at partial state of charge.

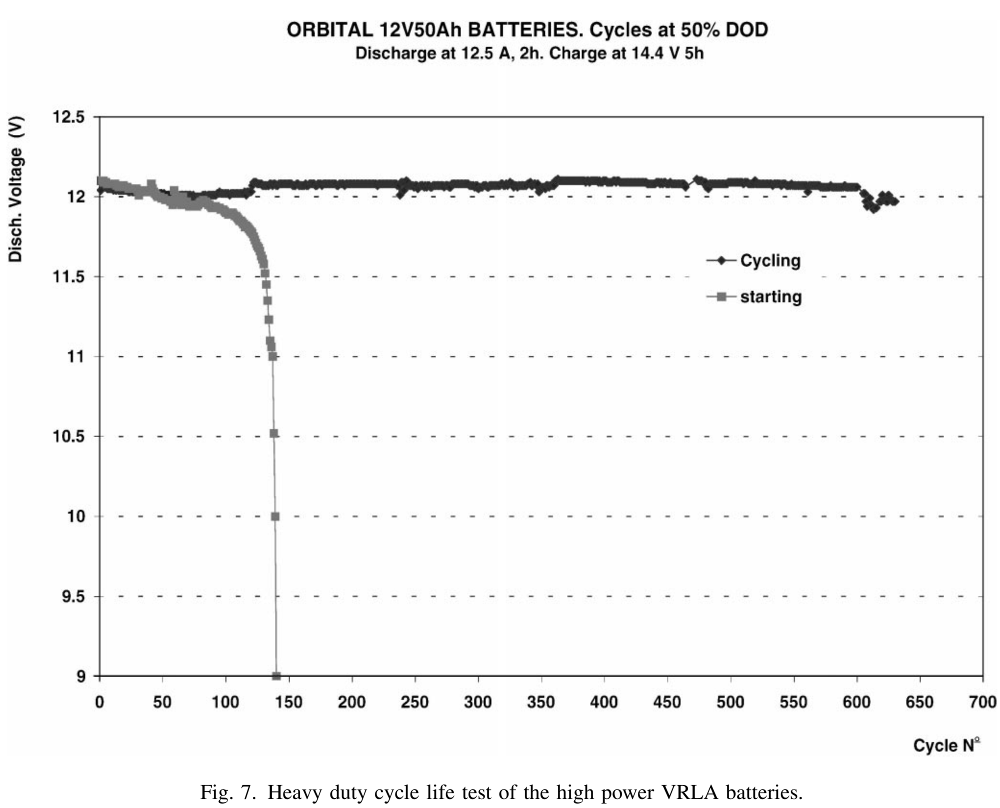


Fig. 7. Heavy duty cycle life test of the high power VRLA batteries.

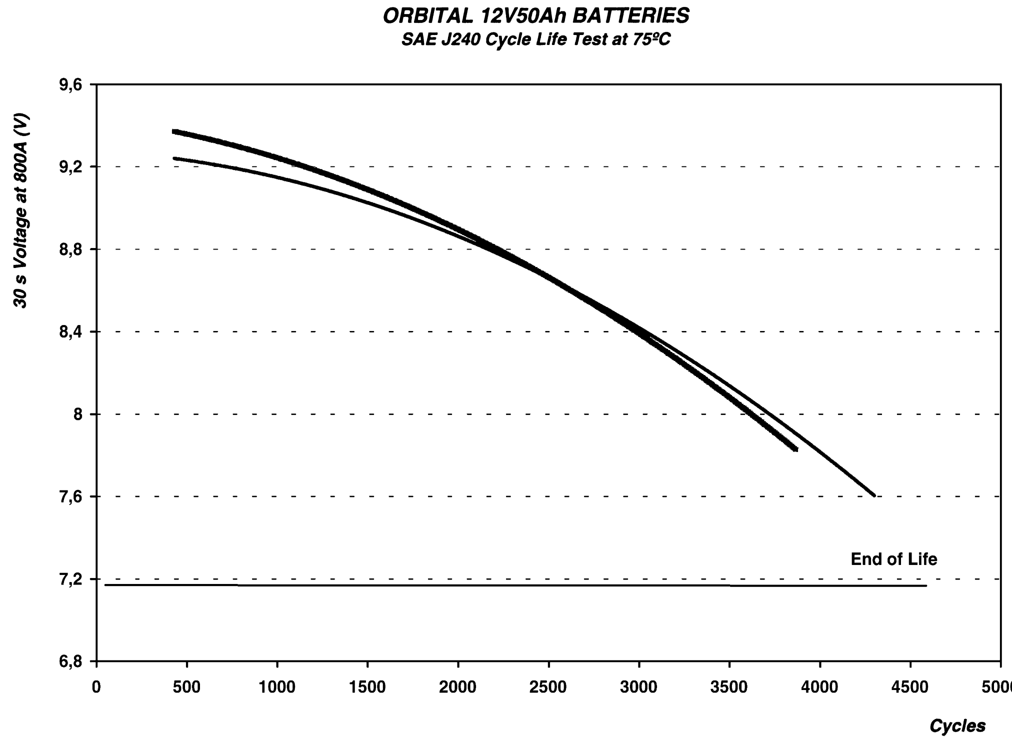


Fig. 8. High temperature (75°C) cycle life test.

1. Discharge 4 min at 25 A.
2. Charge 10 min at 14.8 V (maximum current 25 A).
3. Repeat steps (1)–(2) 430 times.
4. Rest for 68 h.
5. Perform a cranking test at 800 A for 30 s (minimum voltage should be 7.2 V).

The requirement for a 12 V 50 A h battery ranges from 2400 to 3000 cycles. Both batteries passed the test and failed after 4000 cycles. Even though the charging voltage is rather high, water loss is not the only failure mode, but also corrosion of the positive plate. Due to the high corrosion resistance of PbSn alloys, the Orbital batteries behave much better than standard flooded batteries, which fail prematurely due to grid growth taking place with PbCa alloys or high water loss with PbSb alloys.

5. Deep cycle applications

VRLA batteries are the preferred choice for a high number of cycling applications (wheelchairs, cleaning machines, golf carts), that demand high power and maintenance-free products.

Gel technology is a mature technology with proven records of life expectancy under these applications, however, high current performance is the limiting factor due to the higher resistance of the jellified electrolyte.

Absorptive glass mat (AGM) technology has replaced flooded batteries in many stand-by applications due to its higher performance in short-time discharges. However, deep cycle capability of the prismatic designs is limited due to difficulties in maintaining the necessary high compression within the plates.

High power VRLA cells of the cylindrical design with their highly compressed wound plates with large surface area, provide both high current and deep cycle life performances.

5.1. Experimental procedure

Some of the key factors to achieve long cycle life are the porosity of the active mass and the degree of compression. In order to ascertain the design and process parameters which are most appropriate for deep cycle life performance, the following 12 V 50 A h Orbital prototypes were assembled and formed:

- AD1 (very high density positive mass): A special positive mix was prepared with a very high density (5 g/cm^3 instead of 4 g/cm^3), but maintaining all the other process parameters such as separator compression, negative paste and formation process the same as the Orbital starting batteries.
- AD2 (high density positive mass and high compression): With an intermediate positive active mass (4.5 g/cm^3), compression of the separator was increased (from 40 to 50%) by increasing the plate thickness but maintaining the other parameters.
- AD3 (higher plate thickness): With a standard positive and negative mass, plate thickness was increased but

compression was maintained by decreasing the separator thickness by the same amount.

- AD4 (higher amount of active materials): Similarly to the previous test, the amount of active mass was increased maintaining the compression by reducing the separator thickness.
- AD5 (high density positive mass and higher plate thickness): With a similar positive mass density and plate thickness as prototypes AD2, separator thickness was reduced to maintain compression.

Three samples of every group were tested according the following procedure:

1. Discharge 3 h at 10 A.
2. Charge at 14.4 V until the previously discharged amount is recovered (30 A h) followed by 2 h at 1 A.
3. Repeat steps (1)–(2) 50 times.
4. Discharge at 10 A until 10.2 V.
5. Recharge at 14.4 V for 20 h followed by 4 h at 1.25 A.
6. Continue the cycling process in steps (1)–(5) until the discharged capacity is lower than 30 A h.

5.2. Results and discussion

The present test results can be seen in the enclosed Fig. 9, which shows the capacity versus cycle life for the different active material and separator configurations.

High density paste is the key to achieve long deep cycle life, even though compression is also important. The spirally wound design helps to maintain the compression throughout life and, for this reason, too high a density (AD1) or too much compression (AD2) reduces the capacity of the batteries because of acid limitation. On the other hand, thicker plates (AD3) or a higher amount of active materials (AD4), increases the capacity achievable through cycle life. Prototypes with high density positive mass and thicker plates (AD5) performed very well under deep cycling conditions (>1000 cycles at 75% DoD), with the most common failure mode being paste softening and grid corrosion in the upper part of the positive plate. As Fig. 10 shows, the electrical resistance of the battery is increasing throughout the life as a consequence of grid corrosion.

5.3. Conclusion

A goal of more than 1000 deep cycles is achievable by improving paste composition, grid/positive active mass ratio and corrosion resistance (thicker positive grids). Also separator saturation along the height of the plate can be optimised by improving the pore size structure (capillarity) and, in this way, can reduce stratification and provide even further increase in life. Production Orbital deep cycle samples with thicker positive grids and improved paste composition are on testing according

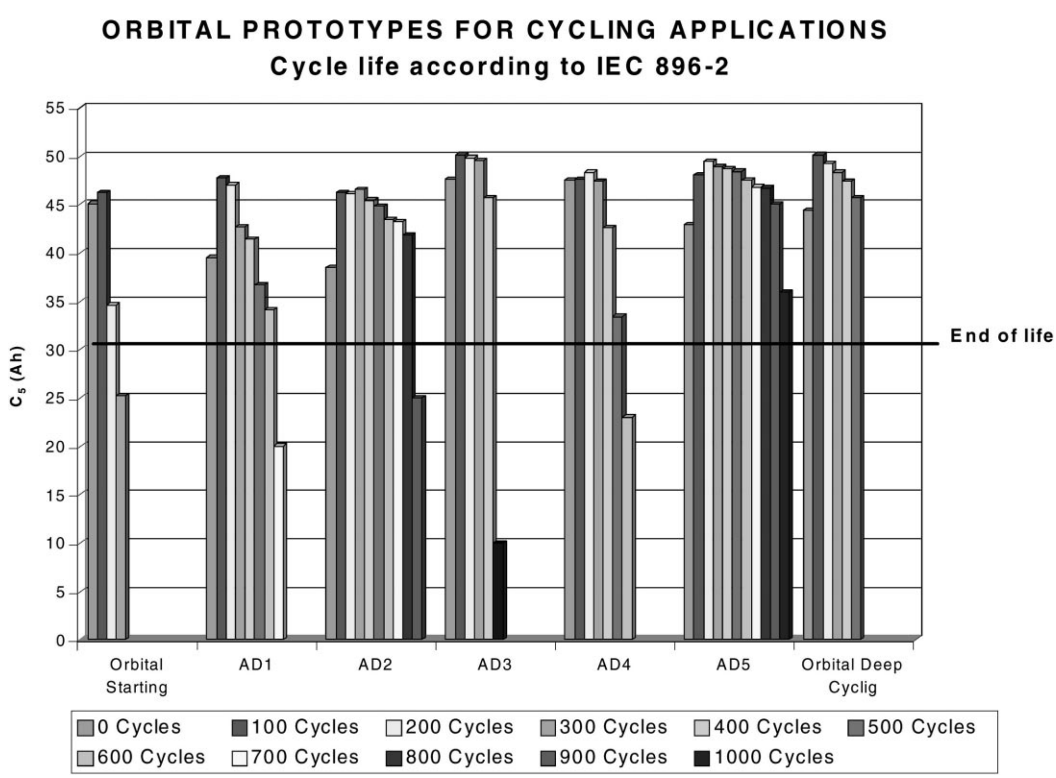


Fig. 9. Deep cycle tests of high power VRLA batteries.

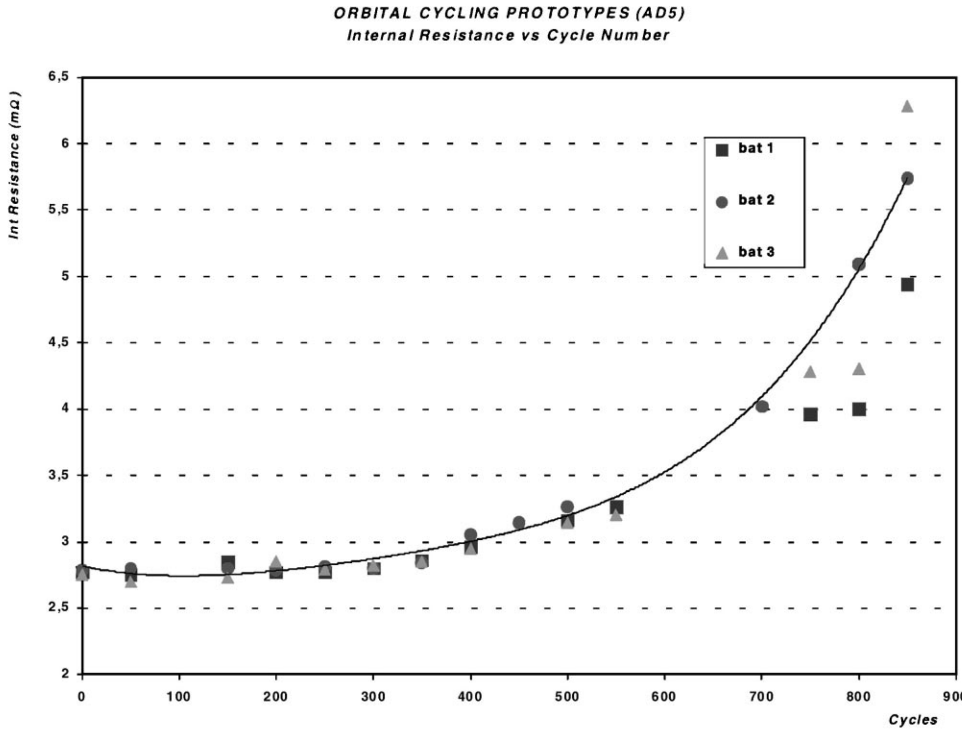


Fig. 10. Internal resistance through cycle life.

to the IEC 896-2 specification. After 500 cycles, the measured capacity is well above the initial value without any sign of grid deterioration (internal resistance is still below 3 mΩ).

6. Charging regime

One of the most important failure modes of VRLA batteries is undercharging that takes place when a certain voltage limit is used in the charge (<15 V) for a relatively short time. It is considered sufficient to recharge about 105–110% of the previous discharge; however, this depends strongly on different parameters such as current, temperature, depth of discharge and time [5].

6.1. Experimental procedure

A batch of Orbital deep cycle batteries was continuously cycled by discharging at 25 A until 10.5 V (BCI specification), then recharged with different charging procedures:

1. IU (15.0 V): Constant current 20 A with a voltage limited to15 V until 110% of the previous discharge is recharged.
2. IU (15.6 V): Constant current 20 A with a voltage limited to 15.6 V until 120% of the previous discharge is recharged.
3. IUi (14.4 V + 1 A2 h): Constant voltage limited to 14.4 V until 100% of the previous discharge is recharged followed by 2 h at 1 A without voltage limit. Every 50 cycles, the batteries are completely recharged according to EN60095-1/A12 (20 h at 14.4 V followed by 4 h at 1.25 A).

6.2. Results and discussion

Fig. 11 shows the influence of the charging process on the deep cycle life of VRLA batteries.

It is clearly seen that charging at constant voltage (15 V), even for a rather long time (up to 20 h), is not sufficient to maintain the capacity (in spite of the rather high recharge factor = 110%). By increasing the voltage (up to 15.6 V), the recharge factor can be increased (up to 120%), with an improvement of the capacity in the initial cycles, but again the capacity decays after some cycling. The higher gassing rate at such a high voltage produces drying out and poor rechargeability of the negative plate, then thermal runaway can take place if the charging is continued. Time to recharge completely (110–120%) varies from the beginning of the cycle test (10–20 h) to the end of the test (2–4 h), depending on voltage limit and the recombination rate. However, charge acceptance at the beginning is very good, because even with rather low voltages (14.4 V), all the previously discharged capacity can be recovered in less than 1 h (providing a high initial current). By adding a small constant current charging period at the end, capacity is maintained better through life without overcharging the battery (recharge factor 105–110%). The increase of capacity after

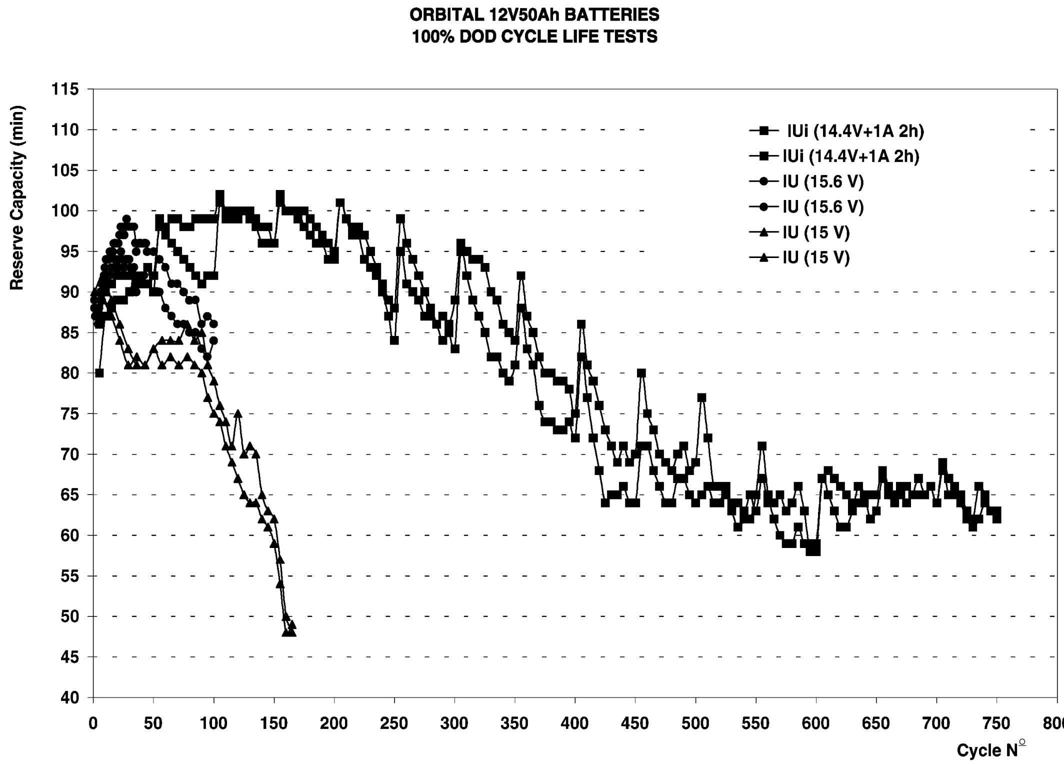


Fig. 11. Influence of the charging process on cycle life.

every complete recharge is also evident, indicating that boosting after a deep discharge is also beneficial for the recovery of full capacity.

6.3. Conclusion

At very high voltages (>15 V), thermal runaway can take place, but low voltages (<15 V), result in undercharging. The best solution, according to our test results, is to equalise the batteries with a small constant current period at the end of charging. With this very simple charging regime — there are chargers in the market that use IUi algorithms — it is possible to achieve more than 700 cycles at 100% DoD.

7. Thermal management

VRLA batteries can be fast charged and discharged, however, in most applications, the charging and discharging rate should be limited because of battery overheating. One of the key features of the Orbital design is the existence of cooling channels in the interstices between the cells. Thermal management can be easily provided by blowing air (or another fluid) through the orifices existing on the top of the battery (see Fig. 2). In order to assess this particular feature of the design, the following test was performed.

7.1. Experimental arrangement

Two Orbital 12 V 50 A h batteries (one for starting and another one for cycling applications) were introduced into a climatic chamber at a constant temperature of 27 ($\pm$2)°C. Both batteries were maintained laying on their sides with the bottom parts in front of the fan blowing air at the specified temperature. The batteries were continuously cycled by discharging at 100 A during 3 min and recharging at 50 A during 9 min with a voltage limited at 14.4 V. Every 1000 cycles, the batteries were completely discharged (at 10 A up to 10.5 V) and then recharged following EN 60095-1/A12 (20 h at 12.5 A with a voltage limited to 14.4 V plus 4 h at 1.25 A without voltage limit). Failure criteria were met when the battery voltage during the partial discharge was lower than 10.5 V.

7.2. Results and discussion

Fig. 12 shows the evolution of the end of discharge voltage with cycling.

Both designs (starting and deep cycle) comply very well with the function required without any difficulty associated with working in the horizontal position. This test aims to simulate a particularly demanding requirement, such as electrically catalytic heaters which required a short-time, high-power discharge and quick recharge in order to be ready for the next discharge. Even though the

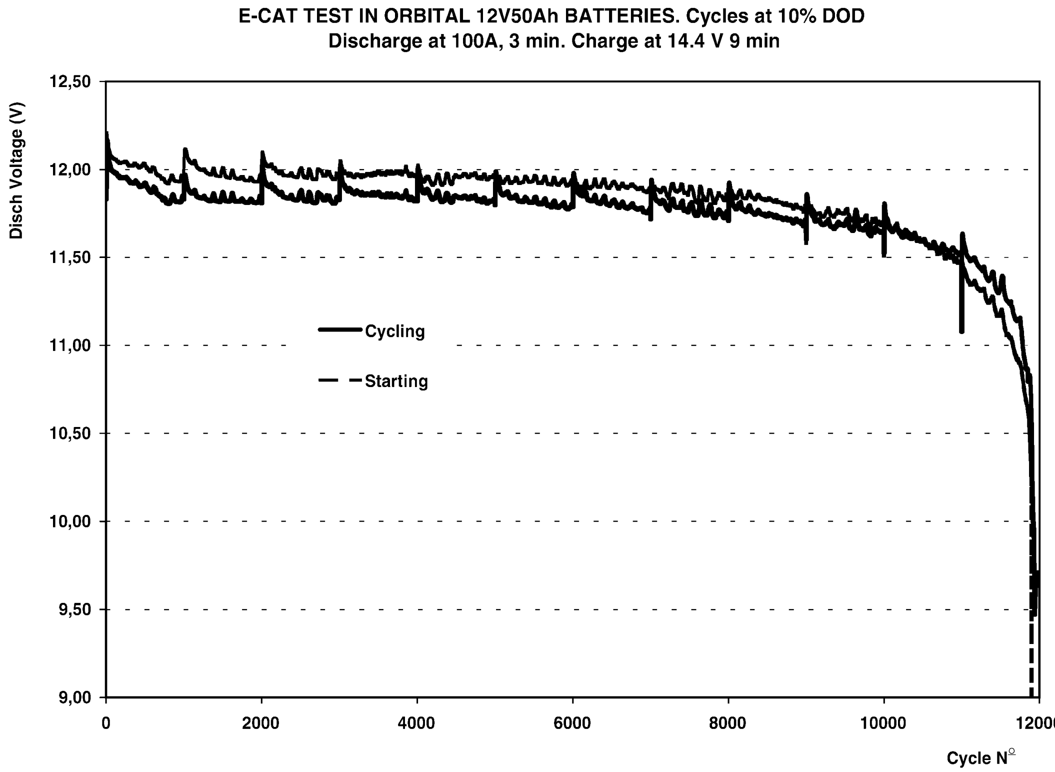


Fig. 12. Shallow cycling of VRLA batteries for electrically heated catalysers.

depth-of-discharge is not very high (about 10%), the intensive use of the battery will require a thermal management system to be installed, for which it could be more convenient to place the batteries on their sides. The orbital design is very well adapted to this application, due to the cooling channels existing between the cylindrical cells. The test was performed by continuously charging and discharging the battery at a rather high current (100 A), thus thermal management become a very important requirement. Blowing air at room temperature (27°C) through the bottom part of the adjacent round cells, is enough to maintain the temperature under 50°C. The amount of charge accepted in every cycle matched exactly that previously discharged (5 A h), and therefore, it was necessary to boost the batteries before a complete discharge took place (in this particular case, a complete recharge was done every 1000 cycles).

At the conclusion of the test, the batteries were opened for teardown analysis. The failure mode was corrosion of the positive grid, which was completely consumed. No other mechanical defect was observed.

7.3. Conclusion

The life cycle achieved (about 12,000 cycles) exceeds the requirement for the life of the car and therefore, the orbital design allows an easy thermal management in the horizontal position, even during the most demanding conditions required by continuously charging and discharging the batteries.

8. Future applications

8.1. Conventional vehicles

The automotive industry is evolving very quickly to lower consumption and to reduce polluting of vehicles and this leads to changing functions for the battery.

In the short-term (2–3 years), new vehicles will be introduced with small electrical motors for booster acceleration and zero-emission at idle. The performance required exceeds the capacities of the present lead-acid system but, with certain improvements in materials and design, high power VRLA batteries can cope with the requirements. New technologies (such as Ni–MH, Li-ion, etc.) will not be ready for these vehicles because of the lack of industrial installations and because the materials cost will make the purchase price prohibitive.

Following the tendency towards cleaner, lighter and cost-competitive vehicles, the main goal of the VRLA batteries is to achieve the requirements of new vehicles for higher specific power and reliability. The main future application of the product in the automotive market, will be as the power source for high voltage systems (42 V networks) with weight and volume substantially reduced, as well as a substantial improvement in cycle life over conventional, flooded, lead-acid batteries. The main failure mode is associated with the positive plate (corrosion and paste softening), and the cylindrical design will be able to overcome these obstacles (by using corrosion resistant PbSn alloys and

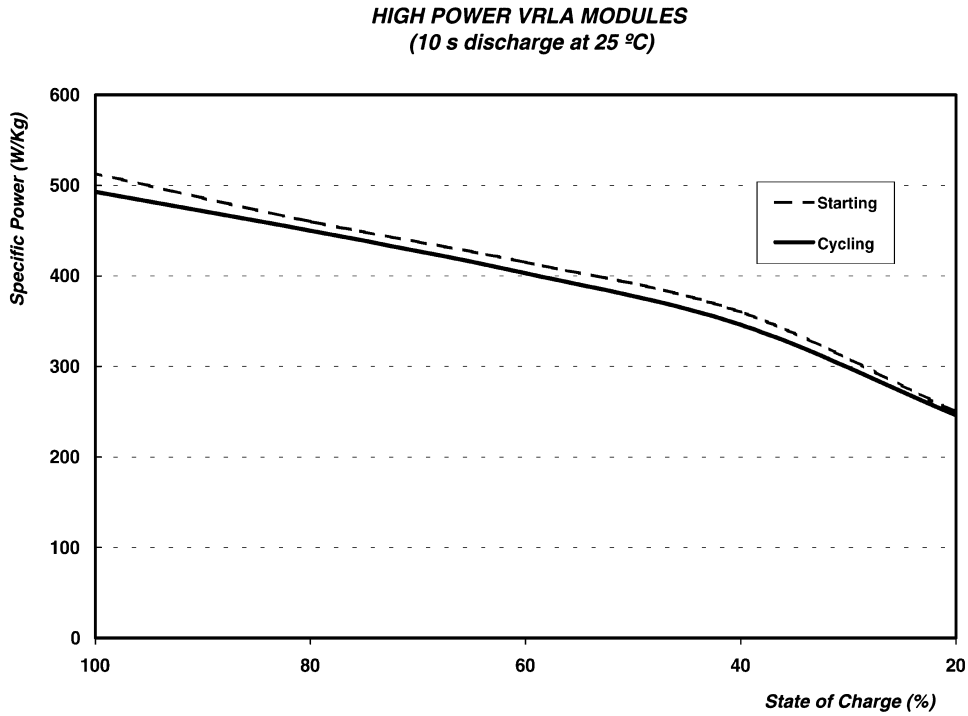


Fig. 13. Specific power of VRLA modules at different states of charge.

constant compression) in order to achieve a more efficient, safe and economic energy supply for the new vehicles.

8.2. Hybrid vehicles

In the medium-term (3–5 years), hybrid electric vehicles (HEV) will require much higher power performance and this will force the introduction of new electrochemical couples. Due to the high cost of raw materials, Ni–MH will be an expensive solution, but technically ready for the new vehicles. Improving the power performance of VRLA batteries throughout the cycle life would give a better opportunity to the hybrid technology to be competitive with conventional vehicles.

VRLA batteries can cope with the high power requirements of HEV at full charge, but the minimum state of charge should be restricted as can be seen in Fig. 13, which shows the decline in specific power with the state of charge. Further reduction through cycle life can be expected due to the fact that grid corrosion will increase the internal resistance.

The advantage of the VRLA technology over other electrochemical couples is that the cost/performance ratio is the lowest, being a practical solution for medium term hybrid vehicles, if the above mentioned disadvantages can be overcome.

8.3. Electric vehicles

In the long-term (6–10 years), the development of new power sources, such as polymer electrolyte membrane fuel cells, will reduce the function of the battery to an auxiliary system to provide short time peak power for acceleration and regenerative braking. The opportunity for new high power devices (either Li-ion or Super-capacitors) will appear. However, the cost will still remain a drawback against improved VRLA batteries.

The new generation of electric vehicles will demand batteries with very high specific power (>500 W/kg) and relatively low specific energy, because most of energy will be supplied by the fuel cell. Due to this fact, it is not necessary to provide energy but power. Battery specific power is, in practice, related to electrode area, so that its increase appears essential to achieve this objective. The high power VRLA batteries are produced by a new continuous process, that will allow, in future, a substantial electrode thickness reduction, from about 1 mm (present value) to around 0.5 mm. Furthermore, it will be necessary to achieve a similar reduction in the conventional glass micro-fibre separator. But such material makes the battery more prone to develop short-circuits across the separator. In order to avoid this problem, new micro-porous membranes are being tested [6,7], due to their promising mechanical properties, high porosity and low pore size.

On the other hand, the decrease in electrode thickness would imply a substantial reduction of power through cycle life, principally because of electrode corrosion. This problem could be avoided by using a proper alloy and by protecting the complete external surface of the grids (full coverage with an orifice pasting machine). Other process parameters that could overcome the peak power decline with life are those related to active material composition (αPbO_2/

βPbO_2 ratio, Pb_3O_4/PbO raw materials) and grid/active mass bond.

It is expected that by overcoming the problems associated with the positive plate performance, high power VRLA batteries would reach the following minimum performances:

Specific power >500 W/kg (10 s discharge at 60% state of charge); fast charge <4 min (from 40 to 80% SOC); calendar life: 3–5 years; cycle life >1000 deep cycles (>60% DoD).

These achievements will not be made at the expense of a higher cost, which should be maintained under the car manufacturers requirements (<150 $/kW h), and as a consequence, high power VRLA batteries will continue to be the most economical approach as the power source of the new vehicles.

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