Journal of Power Sources, 42 (1993) 247–257

Development of a valve-regulated lead/acid battery for automotive use

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Abstract

The use of valve-regulated lead/acid batteries (VRLA) in automotive applications provides some important advantages with respect to traditional flooded designs. Difficulties are reported for flooded lead/acid batteries that use Pb–Ca alloys in the positive grids with respect to recovery of capacity after deep discharge. This problem is no longer valid for recombinant batteries using absortive glass-mat (AGM) separators. Further, this truly maintenance-free battery can be installed in any position, even outside the engine compartment, because of the absence of gas emission or electrolyte spillage. The shelf life is very long and the battery can be stored at open circuit for 12 months with no significant loss of performance. The cold-cranking capacity is higher than the equivalent conventional lead/acid battery due to the reduced internal resistance.

Introduction

Automotive use still is, and will continue to be, the most important and popular application of the lead/acid battery. During the last decade, the widespread introduction of electronics and the increase of electrical loads present in the car has prompted the demand for better battery performance and reliability. On the other hand, the optimization of the car CX coefficient for reducing the fuel consumption has directed the car designer towards the reduction of the engine compartment room, and this has decreased the space available for the battery. As a consequence, the battery is required to be smaller in size (especially with reduced height) without sacrificing overall performance, i.e., the specific energy and power density has to be enhanced.

At the same time, the under-the-hood continuous increase of temperature will affect the battery life. Thus, the availability of an 'install-and-forget' battery to be put anywhere else in the car is highly desirable. In the circumstance, the battery must be truly maintenance free, able to be installed in any position, free from acid spillage and pose no safety hazard due to gas emission. All these requirements are features of the VRLA battery.

The absorptive glass-mat (AGM) or starved technology used for the valve-regulated lead/acid (VRLA) battery has been adopted by FIAMM since the mid-1980s for producing and marketing the Monolite range of batteries for stand-by applications and, more recently, a range of small batteries has been developed for consumer applications. The know-how gained has enabled FIAMM to start a development activity that has culminated in demonstrating the feasibility and performance of a VRLA battery for automotive applications.

0378-7753/93/$6.00

Battery design

The core of a VRLA battery that adopts the starved technology is the absortive glass separator. This serves the double function of retaining the electrolyte necessary for the discharge reaction, and of allowing the oxygen generated at the positive plate during charging to migrate to the negative plate where the recombination reaction takes place. Another important feature is the plate separator compression that is necessary to ensure good electrolyte conductivity between the plates and the separators. This, in turn, provides a better retention of the positive active material to the grid; a feature that is particular beneficial when using – as in the case of VRLA batteries – a Pb–Ca positive grid.

By design, the VRLA battery has a reduced amount of electrolyte, and this causes a reduction in the slow-rate capacity compared with that for a flooded counterpart. This problem is only partially recovered by increasing the electrolyte density. On the other hand, the inherent lower internal resistance of the AGM separator enhances the cold-cranking capacity of the VRLA battery versus the flooded one.

A further important difference with the VRLA design is that the strength of the container must be increased in order to provide an adequate compression of the plate groups throughout the battery life and to withstand the internal positive venting pressure of the one-way valve fitted to each cell. FIAMM has selected two popular battery configurations for development, the L2 and L3 sizes with a low profile (175 mm high).

In order to maintain the advantages of polypropylene as a container material, this has been strengthened by the addition of two filling materials (namely, $CaCO_3$ and talc) and by designing the end walls through a finite element approach with a VAX 8600 computer in such a way to obtain a reinforced structure. The latter is shown in Fig. 1. The ability of the container to withstand increasing internal pressures at various temperatures for the two different filling materials is shown in Figs. 2 and 3. It is clear that the talc-filled polypropylene material exhibits the better mechanical resistance.

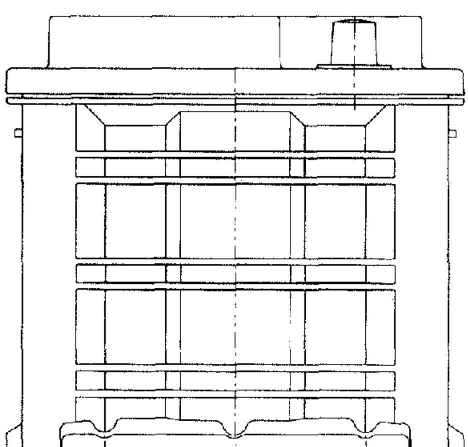


Fig. 1. Reinforced end wall of L2 and L3 VRLA automotive batteries.

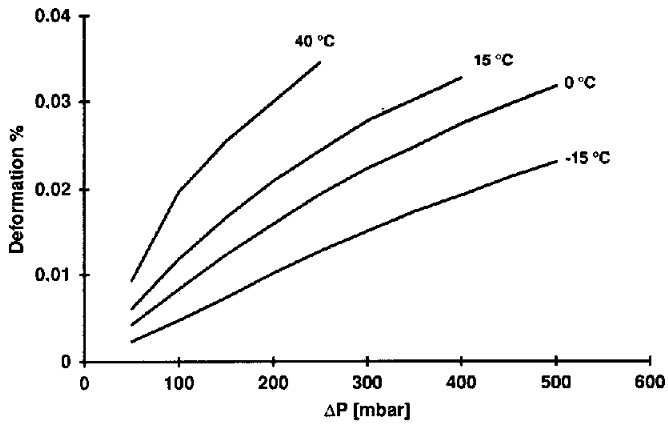


Fig. 2. Reinforced L-type case deformation vs. internal positive pressure differential at various temperatures; case material: polypropylene filled with $CaCO_3$.

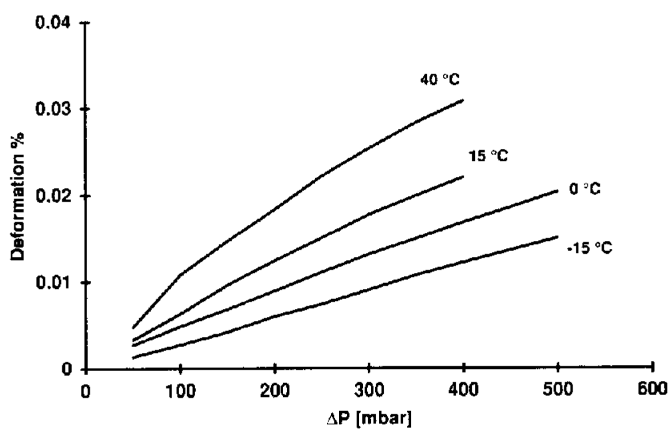


Fig. 3. Reinforced L-type deformation vs. internal positive pressure differential at various temperatures; case material: polypropylene filled with talc.

Table 1 and Fig. 4 summarize the dimensions and performances of the European L-size battery range: the L2 and L3 VRLA battery dimensions comply with the standard, but with a reduced height (175 mm).

Battery performance

Electrical characteristics

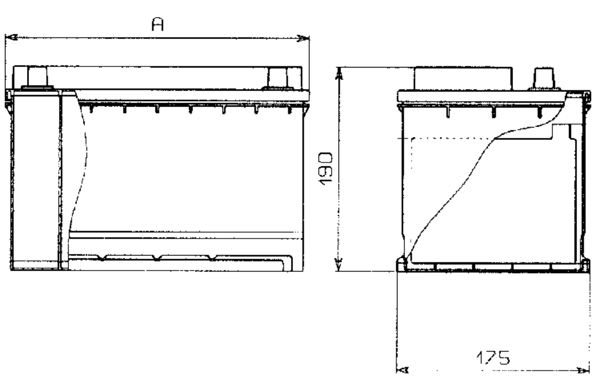
Table 1 compares dimensions, weight and specific performances of FIAMM flooded and VRLA L2 and L3 automotive lead/acid batteries. As anticipated, the slow-rate capacity and the reserve capacity are higher for the flooded batteries, while the cold-cranking current is by far superior for the VRLA. Specific capacities (A h kg^{-1}, A h dm^{-3}) are comparable but specific power related figures (A kg^{-1}, A dm^{-3}) are

TABLE 1

Dimensions, weights and performances of FIAMM flooded and VRLA L2 and L3 automotive batteries

Type	Flooded		VRLA	
	L2	L3	L2	L3
Dimensions				
length (mm)	242	278	242	278
width (mm)	175	175	175	175
height (mm)	190	190	175	175
Capacity C_{20} (A h)	60	70	53	60
Reserve capacity (min)	105	138	95	120
CCC[a] (A)	320	400	400	450
Weight (kg)	15.7	19.5	16.5	18.6
Specific capacity				
(A kg^{-1})	20.38	20.51	24.24	24.19
(A h kg^{-1})	3.82	3.59	3.21	3.23
(A dm^{-3})	39.77	43.27	53.97	52.86
(A h dm^{-3})	7.46	7.57	7.15	7.05

[a]Current sustained at −18 °C for a minimum of 75 s to an end discharge voltage of 7.2 V and voltage after 10 s >9.1 V.



Type	A (mm)	Weight (kg)	C_{20} (A h)	CCC[a] (A)	Reserve capacity (min)
L0	175	10.5	40	210	60
L1	207	13.9	50	275	87
L2	242	15.7	60	320	105
L3	278	19.5	70	400	138

[a]Current sustained at −18 °C for a minimum of 75 s to an end discharge voltage of 7.2 V and voltage after 10 s >9.1 V.

Fig. 4. L-size European automotive battery range. Dimensions, weights and battery performances.

TABLE 2

Cold-cranking performances of L2 and L3 VRLA automotive batteries according to DIN, SAE and new Eurobat specifications

Test type	DIN		SAE		Eurobat	
	L2	L3	L2	L3	L2	L3
A	340	380	670	720	700	750
V at 10 s	9.62	9.71	7.72	7.95	7.85	7.98
A kg^{-1}	20.61	20.54	40.61	38.92	42.42	40.54
A cm^{-2}	0.142	0.139	0.279	0.263	0.292	0.274

better for the VRLA types. Table 2 also compares the performances of the L2 and L3 batteries according to DIN, SAE and the new Eurobat specifications.

Endurance test

The endurance characteristics of the VRLA L3 battery was tested following modified SAE, PSA BSESA and DIN endurance tests. Details of the test conditions are given in Table 3. The results in Fig. 5 report the time to 7.2 V of the cold-cranking test performed after an increasing number of modified SAE cycles. It is shown that more than the required number of cycles were obtained.

The behaviour of the same battery tested according to the PSA BSESA endurance test is presented in Fig. 6. Again, the specification requirements for 4 units were easily met and exceeded. Finally, the results of the DIN endurance test are reported in Fig. 7 for the VRLA L3 battery and the specification requirements are again largely exceeded.

Self-discharge

One very important feature of the VRLA battery — which is of course a 'wet' battery — is its ability to retain capacity over extended periods of open-circuit stand.

Figure 8 shows the open-circuit voltage decrease of a group of four VRLA L3 batteries kept at open circuit at 25 °C. The cold-cranking capacities retained by each battery of the group was tested after 4, 8, 12 and 18 months. Soon after discharge, the batteries were recharged and the cold-cranking capacity measured again. Figure 9 shows the voltage after 10 s of discharge of the battery maintained at open circuit for different lengths of time with no recharge and after recharge. Figure 10 shows the time of discharge to 7.2 V for the same battery. The ability of the battery to start a car even after 18 months of open-circuit stand with no recharge is apparent. It is also demonstrated that the cold-cranking capacity is almost completely recovered after recharging.

It is well known that long open-circuit stand induces irreversible damage to the battery. To evaluate how such periods may affect the battery condition a battery was tested according to a modified SAE J-240 life test after 12 months stand at 25 °C. As indicated in Fig. 11, a 12-month old battery is still capable of meeting the specifications.

Truly maintenance-free characteristics are another essential feature for a 'install-and-forget' battery. To test the ability of the VRLA battery to retain high recombination efficiency and then low water consumption on overcharge, even after a long store at open circuit, a battery was tested for its water consumption after standing for 18

TABLE 3

Endurance tests for automotive batteries

Test		Current (A)	Voltage (V)	Time (min)	Temperature (°C)	Requirements
J-240 SAE modified	Charge	25	14.8	10	40	After (70 time C_{20}) cycles
	Discharge	25		4		Time of CCT to 7.2 V > 30 s
PSA-BSESA	Charge	$0.2 \times I_{cc}$	14.8	4	40	One unit of CCT, 2160 cycles
	Discharge	$0.03 \times I_{cc}$		2		After 4 units, time of CCT to 7.2 V > 30 s
DIN 43539 Part 2	Charge	$5 \times I_{20}$	14.8	300	40	One-week cycling, one unit
	Discharge	$5 \times I_{20}$		120		After 5 units, time of CCT to 7.2 V > 30 s

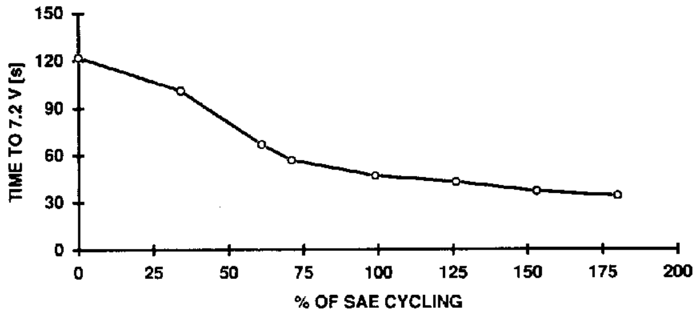


Fig. 5. Time to 7.2 V of cold-cranking tests (450 A at −18 °C) during modified SAE cycling test; lower limit = 30 s; 100% = 4200 cycles.

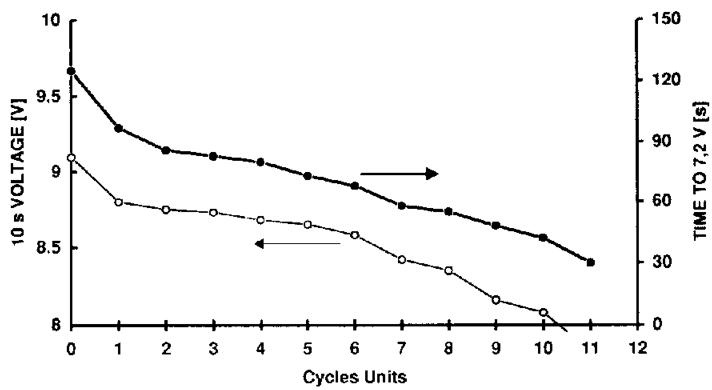


Fig. 6. 10 s voltage and time to 7.2 V of cold-cranking tests (450 A at −18 °C) during PSA-BSESA endurance test for a VRLA L3 battery.

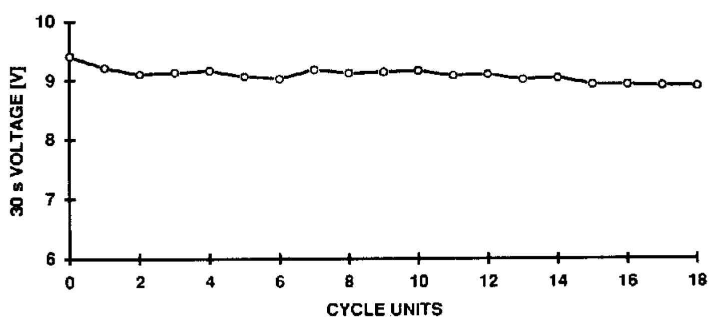


Fig. 7. 30 s voltage on cold-cranking tests (380 A at −18 °C) during DIN endurance test for a L3 VRLA battery.

months. The results, summarized in Table 4 and Fig. 12, show the ability of the battery to maintain good recombination efficiency (exceeding 99%) and cold-cranking performance.

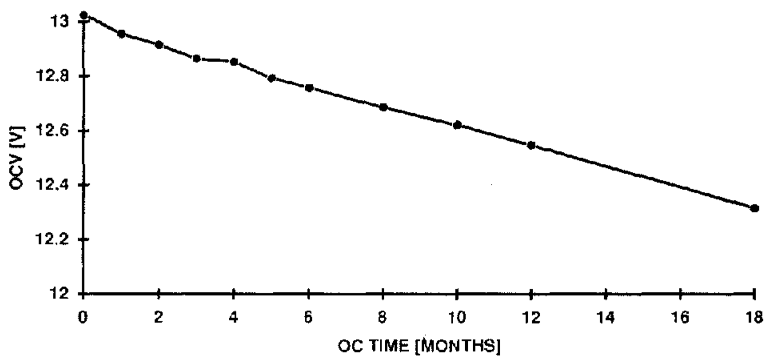


Fig. 8. Open-circuit voltage vs. time of L3 VRLA battery at 25 °C (average value of 4 batteries).

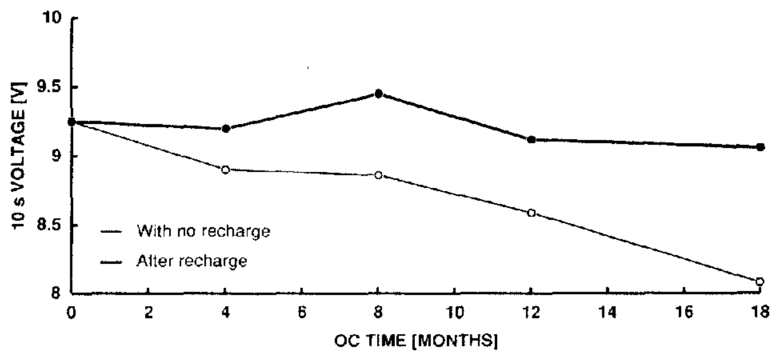


Fig. 9. 10-s cold-cranking voltage of L3 (−18 °C) VRLA battery with no and after recharge vs. open-circuit stand.

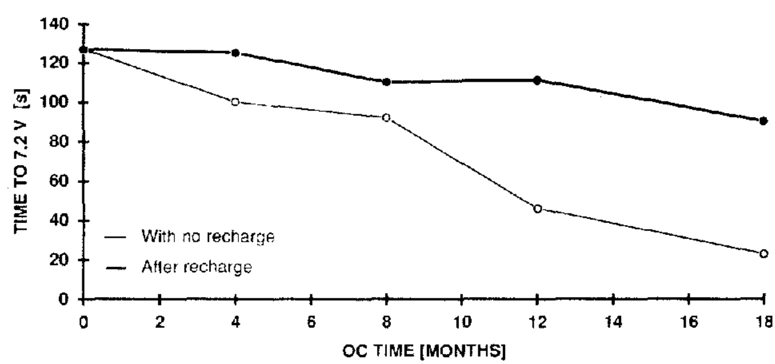


Fig. 10. Cold-cranking time (−18 °C) to 7.2 V of L3 VRLA battery with no and after recharge vs. open-circuit stand.

Ability to recover capacity after deep discharge

The problems encountered with flooded Pb–Ca automotive batteries in terms of capacity recovery after a deep discharge are widely recognized. To test the ability of a VRLA automotive battery overcome this difficulty, a L3 battery was fully discharged

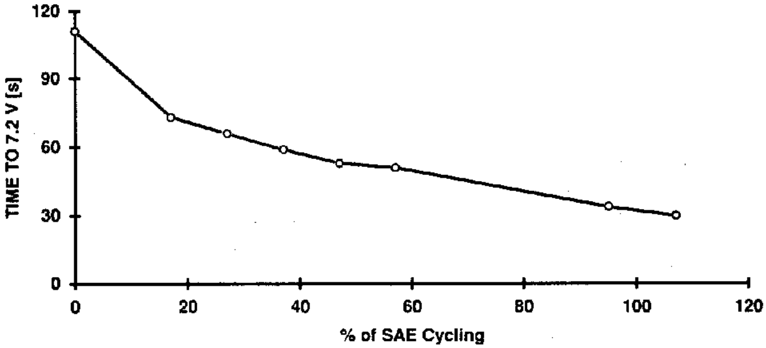


Fig. 11. Cold-cranking discharge time (−18 °C) to 7.2 V of a L3 VRLA battery tested according to modified SAE J-240 life test after 12 months of open-circuit stand vs. number of cycles.

TABLE 4

Water consumption of a L3 VRLA battery overcharged at 14.4 V and 40 °C after 18 months of open-circuit stand

Time (h)	Over charge (mA $(Ah)^{-1}$)	Weight loss (g $(Ah)^{-1}$)
500	8.8	0.2
1000	10	0.25
2000	8.8	0.32

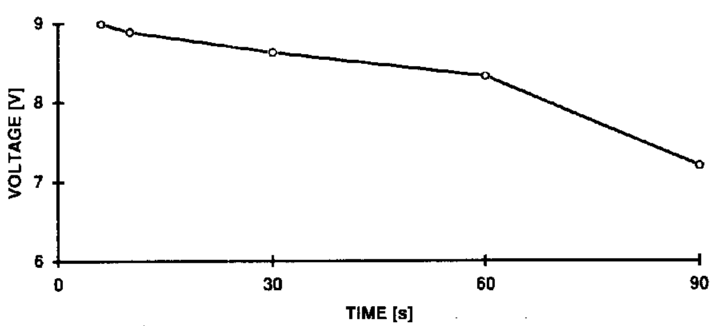


Fig. 12. Cold-cranking test (450 A at −18 °C) of a L3 VRLA battery after 18 months of open-circuit stand and 2000 h of overcharge at 14.4 V, 40 °C.

and then maintained for 7 days on discharge across an electrical load of 10 Ω. After recharge, the battery was tested for its reserve and cold-cranking capacities. Both were recovered to more than 90% of their initial values.

Charge acceptance test

A VRLA L3 battery was discharged at 25 A for 0.8×reserve capacity minutes, following the SAE J537 specification. After cooling down to 0 °C, the battery was recharged at 14.4 V and after 10 min of recharge, the current acceptance was 15 A compared with a required minimum of 9 A.

Field test

A field test of the VRLA L3 battery was conducted by the taxi fleet in the town of Vicenza. The taxi population comprised 27 vehicles of different makes and ages. The batteries were installed with no attempt of adjusting the alternator voltage setting. Table 5 summarizes the results after 12 months of testing. Details are given of the individual taxi mileage, together with the weight loss and cold-cranking performance

TABLE 5

12-months field test of VRLA L3 batteries in taxi fleet

Battery no.	Car voltage setting (V)	km	Battery weight loss (g)	Discharge time to 7.2 V (450 A at −18 °C)	
				With no charge (s)	After recharge (s)
301	13.85	70000	−10	66	94
302	13.80	84300	−12	80	92
305	14.04	52800	−60	41	73
306	14.00	62600	−40	45	51
311	13.90	62300	−50	33	44
312	14.01	9500	−21	70	104
313	14.01	51600	−21	64	88
314	13.90	89500	−4	66	85
315	14.02	77500	−16	69	108
316	13.63	25600	−8	74	105
318	13.95	27800	−13	58	90
319	13.90	97600	−15	55	84
320	14.01	72700	−21	39	47
321	13.90	58600	−46	10	46
323	13.85	87700	−18	0	73
324	13.50	85000	5	80	93
326	14.10	11300	−10	61	93
327	13.70	53600	−31	67	73
328	13.90	68700	−16	55	90
330	13.70	75400	−17	48	68
331	14.05	74800	−19	58	85
332	13.98	63900	−27	30	65
333	14.23	39300	−77	84	87
334	14.02	32400	−22	55	92
335	13.85	64100	−55	33	61
337	13.85	69000	−18	23	87
338	13.90	46300	−10	41	93
339	13.86	68800	−50	65	72
340	13.75	88000	−14	50	64
342	13.93	41400	2	76	73
Average	14	60403	−24	53	79
Minimum	13.5	9500	−77	0	44
Maximum	14.23	97600	5	84	108

of the batteries tested in the laboratory with no recharge and after recharge. All the batteries performed well in spite of the different mileages and voltage settings. These results demonstrate the ability of a VRLA battery both to withstand and to cope with different and severe service conditions. The field test is still in progress; no battery failures have occurred after 22 months of the project.

Conclusions

The advantages of a VRLA battery for automotive applications as compared with its flooded counterpart can be summarized as follows:

- reduced size, resulting in a low-profile battery due to the fact that the electrolyte over the plates is no longer needed
- higher cold-cranking rate due to its inherent internal resistance; where circumstances do allow (slow-rate capacity requirements not prevailing) this may allow the use of smaller batteries
- more than adequate service life as demonstrated through the endurance witnessed in both laboratory and field tests
- very low self-discharge on open-circuit stand, which also makes the battery suitable for the aftermarket
- truly maintenance-free behaviour
- virtually no emission of acid which prevents the corrosion of the battery terminal posts, as well as other devices surrounding the battery that are exposed to corrosive attack
- no explosion hazard because the emission of explosive gases is virtually eliminated

Among the drawbacks of the battery, the reduced slow-rate capacity due to the reduced amount of electrolyte appears to be the most relevant. As to the behaviour of the VRLA battery at high under-the-hood temperatures, tests are still in progress; it can be anticipated, however, that the battery will behave very similarly to the flooded equivalent.

The main advantage of the VRLA automotive battery is of course represented by the possibility of installing the battery outside the engine compartment. This opens up a number of new options and problems for the car designers. It is believed that the new battery technology will help them to meet some of the requirements posed by modern car design.

Acknowledgements

A working group was established for this project. This group carried out most of the tests and analysis of the results. The group was composed of the authors together with the following other contributors: G. Baudo, M. Caselli, L. Chiarello, O. Gobbo, D. H. McClelland, M. Ottaviani and S. Rudilosso.