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A new valve-regulated lead/acid automotive battery for use in original equipment and supply to the replacement market

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Abstract

Valve-regulated lead/acid (VRLA) batteries have been available since the beginning of the 1970s for stationary applications. Nevertheless, the development and the commercialization of VRLA starter batteries have been very slow and mainly restricted to certain niche markets. This is due to the difficulty in designing products that comply with the technical specifications required by the operating conditions of modern cars, and that have both a high level of reliability and a cost in accordance with the needs of the automotive market. The STR (sealed technology with gas recombination) battery has been developed in order to place on the automotive original equipment and replacement markets a battery with the benefits of the VRLA technology, namely: absolutely no maintenance; clean and safe; good open-circuit storage; good cycling ability; performance comparable with that of flooded batteries (i.e., cranking power and reserve capacity, charge acceptance, rechargeability, and life). Due to the technical choices made for the components and for the manufacturing process, the STR battery is today manufactured on a production line very similar to that for a flooded battery, with a good level of productivity and the same reliability as the best flooded batteries. For all these reasons, the STR battery is produced at a cost that is acceptable for automotive applications. © 1997 Published by Elsevier Science S.A.

Keywords: Valve-regulated lead/acid batteries; Starter batteries; Life tests

1. Introduction

The concept of a valve-regulated lead/acid (VRLA) battery with gas recombination is a relatively old one. The battery is designed to recombine, on the negative plates, the oxygen evolved from the positive plates during charging or overcharging. This can be achieved by using a special cell design with either starved electrolyte and an absorptive glass-mat separator, or with gel electrolyte. Each design allows rapid diffusion of the gaseous oxygen inside the battery, from the positive to the negative plates.

Valve-regulated lead/acid batteries have been developed since the beginning of the 1970s for stationary applications. Initially, only small-capacity batteries were produced but, during the last twenty years, these types of batteries have secured a large part of the stationary battery market. During the same period, the development and the commercialization of VRLA starter batteries have been very slow and mainly limited to niche markets such as military batteries or hobby batteries (camping, caravaning, boating, etc.). The main reason for the restricted success of VRLA starter batteries, despite their many technical advantages, is the difficulty in designing products that comply with the technical specifications required by the operating conditions of modern cars, and that have both a high reliability level and a cost in accordance with the needs of the automotive market.

In introducing the work reported here, it is important to establish the main benefits of the VRLA design for starter applications. These benefits depend on the market — the original equipment market (OEM) or the replacement — market for which the battery is destined. This is due basically to the fact that the needs of the two markets are not exactly the same, but also because for the OEM, the advantages of a new battery type can be integrated into new car designs.

1.1. Original equipment market advantages

1.1.1. Totally maintenance-free battery

The recombinant process renders VRLA starter batteries completely maintenance-free. This is an improvement for the user, but it can also lead to a reduction in the scheduled maintenance operations of the car. For car designers, the recombinant battery can be located in less-accessible places of the car.

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1.1.2. A safe and clean battery

Due to the absence of free electrolyte, a VRLA battery is safe and clean and without acid spillage or fume emission during both handling and operating conditions. This characteristic is very important in terms of battery location. For instance, it allows the battery to be situated either in the trunk or in the passenger compartment without risk to the passengers or the environment. This feature may be requested for modern cars due to the lack of room in the engine compartment. For the same reason, it also enables the battery to be placed in the vicinity of electronic components, for instance, in a cooled area. Finally, the valve-regulated design gives more flexibility during vehicle assembly because it can be handled in various orientations without acid spillage.

1.1.3. A battery easier to recycle

At the end of battery life or car life, batteries must be recycled. The absence of free electrolyte simplifies the transport of batteries to the smelter.

1.2. Replacement market advantages

Some of the advantages of VRLA technology outlined above for the starter battery OEM (i.e., maintenance-free characteristics, cleaness, recycling ability) are also advantages for replacement batteries. One of the main interests in VRLA design for the starter replacement market is that this type of battery is a very good trade-off with respect to flooded and dry-charged traditional batteries. On the one hand, dry-charged batteries have a good storage ability and a good transportation ability, but require sulfuric acid handling during the activation operation. On the other hand, flooded batteries are ready for use but acid spillage can occur during handling and transportation. Valve-regulated batteries offer the advantages of both types of traditional batteries and, therefore, are very well suited to the new distribution networks (such as supermarkets) and to installation in the car directly by the user.

Because of all theses advantages and due to an increasing demand for such properties, the STR battery has been developed in order to put on the automotive market a VRLA unit that complies with both the technical and the economical requests of this market.

2. Battery construction

2.1. Choice of technology

At present, two technologies are available for VRLA batteries: the gel technology that involves gelling the electrolyte by the addition of a certain quantity of silica, and the AGM (absorptive glass mat) technology in which the electrolyte is immobilized in a very porous and absorbant material such as glass microfibres. The recombination cycle takes place via oxygen transfer through the gel or the separator, in a sealed cell.

Both VRLA technologies are produced by the CEAC group and a comparison has been made in terms of economical and technical aspects. The main difference between the two types of batteries is the grid-manufacturing process, i.e., rolled expanded metal for AGM versus gravity-cast metal for gel. The technical comparison has been carried out mainly on the properties listed in Table 1. The choice of the AGM technology was justified by the superior behaviour exhibited under the severe conditions that occur in cars (i.e., overcharge at high temperature) and under corrosion tests. Moreover, the gel technology is generally produced at a higher cost, which is partially due to the more complicated plate-formation process.

2.2. Product design and production process

The technical choices made for the STR battery were intended to achieve performances in accordance with the requirements of the different specifications for automotive applications, and to produce the battery at minimal production cost.

2.2.1. Plates

The alloy used for VRLA batteries is a lead–calcium system in order to ensure a low self-discharge rate and to prevent excessive evolution of hydrogen in the battery. The same type of alloy has been retained for the STR battery. Negative grids are made from standard lead–calcium, while positive grids use a special alloy. The latter alloy has been developed with an addition of tin in order to give the battery a better rechargeability. The grid-manufacturing process, which is the rolled expanded metal technique, gives all the benefits of a continuous process such

Table 1
Comparative tests between AGM and gel technologies with reference to lead–calcium flooded batteries

Parameter	AGM	Gel
20-h rate capacity	−15 to −20%	−15 to −20%
Reserve capacity	same	same
Cold-cranking at −18 °C		
Voltage after 10 s	same	−0.5 V
Duration	−15%	+10%
Charge acceptance	same	same
	(according to OE requirements)	
Storage		
State-of-charge after 18 months at 20 °C	same	+10%
Corrosion	same	same
Recombination rate	>95%	>95%
Overcharge at 40 °C (Reference 3500 h in liquid battery)	+500 h	−1000 h
Endurance in cycling test (European 'original equipment' specification)	same	same

as a constant grid thickness and a constant weight with a high level of productivity.

For good operation of the battery, it is necessary to have homogeneous compresssion across the plate surface. The choice of the expanded-metal process for positive and negative grids was taken to ensure a constant thickness of the plates and also to provide the benefit of a continuous process that maintains a good level of productivity for the manufacturing process. The paste is made with a standard process; curing is conducted at high temperature.

2.2.2. Separator

For flooded automotive batteries, the separator is made from polyethylene sheet that is welded on both sides. This allows a high production speed and a reliable enveloping process. For AGM batteries, the separator is generally made from 100% glass-microfibre material. This is adapted from the specifications for stationary batteries, with a good wicking rate and a high absorbant power, but with a low mechanical resistance. As a consequence of this fragility, the complex process of enveloping and stacking involves lower production speeds and creates difficulty in handling the thin separators.

The main purpose of the study into a new separator was to develop a material that is a compromise. A new separator has been developed in order to increase the mechanical strength of the glass-microfibre material, and to make envelopes that are welded along the sides by either an ultrasonic or a knurling process to give the same productivity and, especially, high reliability in the enveloping and stacking processes as found with polyethylene separators. The separator is made from a mix of glass and organic microfibres and has roughly the same absorption properties as the traditional type that contains 100% glass microfibres.

2.2.3. Cell group

The cell group is automatically assembled and welded. The alloy used for the straps is a tin-rich, antimony-free alloy. To ensure a weld of good quality, the lugs are pre-tinned. The STR design is shown in Fig. 1.

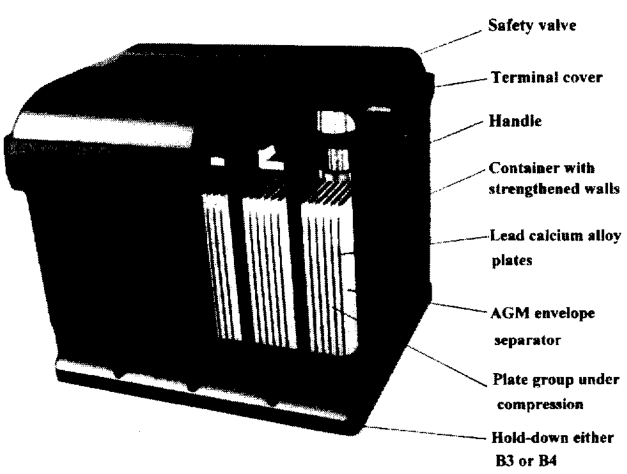

Fig. 1. STR group.

2.2.4. Plastic parts

Generally, the plastic parts of starter batteries are made with polypropylene (PP) of a thin-wall construction. For stationary batteries, due to the high compression rate of the group and to the risk of high internal pressure, the containers are made with a more rigid material such as acrylonitrile/butadiene/styrene (ABS) or PP mixed with talc in a thick-wall construction.

For economic reasons and due to the poor resistance of materials such as ABS or talc-filled PP to thermal shock, it was decided to stay with a standard material, such as the PP used in starter batteries, and to adjust the thickness of the wall to meet the required specifications. A mathematical model was used to calculate the wall deformation at different wall thicknesses. This took into account the mechanical characteristics of the material and the internal pressure (defined as the maximum opening pressure of the valve). The resistance against deformation obtained by increasing the external wall thickness was roughly the same as with a lower thickness (equal to that of starter batteries) and a PP mixed with talc, but is a more expensive solution.

The lid is also made with a standard PP. A cover is placed over the valves and heat welded at different points to prevent access to the valves and, therefore, to prevent the addition of water that could have a detrimental effect on the safety properties of the battery.

The same type of calculation that was used for the container was also employed to determine the optimized shape and thickness of the handle. The purpose of this study was to forecast the displacement and the stress of the handle when it is submitted to a definite weight associated with a certain acceleration (Fig. 2). This model has been used for different materials. The choice was made in terms of the material that gave the best compromise between the technical specifications (mechanical resistance, ergonomics, resistance to thermal shock, etc.) and the cost and industrial requirements. The same study was carried out for the anchor system of the handle.

2.2.5. Valve

The valve used on the STR battery was chosen from among the many different systems that already existed in the CEAC group. A comparative study of the advantages and disadvantages of each system was performed according to the following aspects: technical, quality, reliability, manufacturing, economic and safety. The choice that was made for the STR batteries was not the cheapest, but was motivated by a real concern for reliability given the importance of the role played by this component (gas recombination, self-discharge, safety). The valve is manufactured by Sonnenschein and has been used in VRLA batteries for almost 20 years for stationary, traction and automotive applications (military, buses, leisures, etc.). The valve (Fig. 3) is composed of an assembly of different pieces (membrane, body, lid, plug) that allows control of the main characteristics — opening and closing pressure, tightness — during the different steps from the valve production to its assembly in the battery.

2.2.6. *Design of battery*

The design of the STR battery was esthetically developed by a consultant following a market survey with different types of consumers. The handle system is simple and safe. The handle and the terminal cover can be removed easily should it not be possible to leave them in the car. A special design has been developed for some OE customers and has the same types of handle that are presently used for flooded batteries.

3. Battery performance

3.1. *The after-market range*

The after-market range is described in Table 2. This range, if compared with the flooded-elecrolyte equivalent for the same weight of lead, yields a lower capacity but the same cold-cranking ability and the same reserve capacity. The lower active-material utilization is due to the limited quantity of electrolyte, which is all absorbed in the separator.

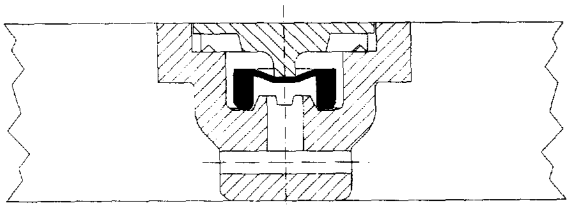

Fig. 3. Sonnenschein valve.

3.2. *Cold-cranking ability*

3.2.1. *At different states-of-charge*

A comparative test of the cold-cranking ability of flooded and STR batteries has been carried out for different states-of-charge. The initial capacity was 70 Ah for flooded and 65 Ah for STR batteries. The batteries were

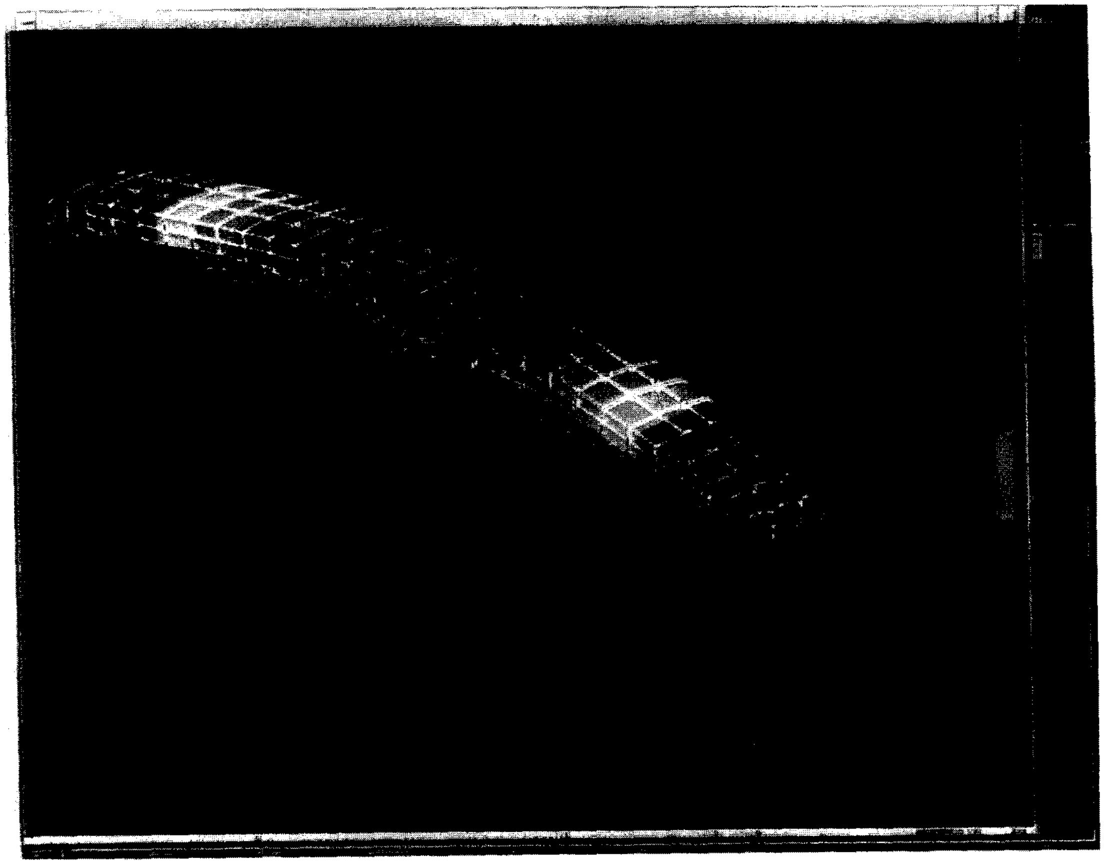

Fig. 2. Modelling of the handle.

discharged for a set number of Ah, i.e. 14, 28 and 35 Ah. The results are given in Table 3.

After discharge, the batteries were submitted to a cold-cranking test at −18 °C for three successive cycles that each comprised 10 s discharge followed by 10 s pause. The results (see Fig. 4) show that the voltages obtained on

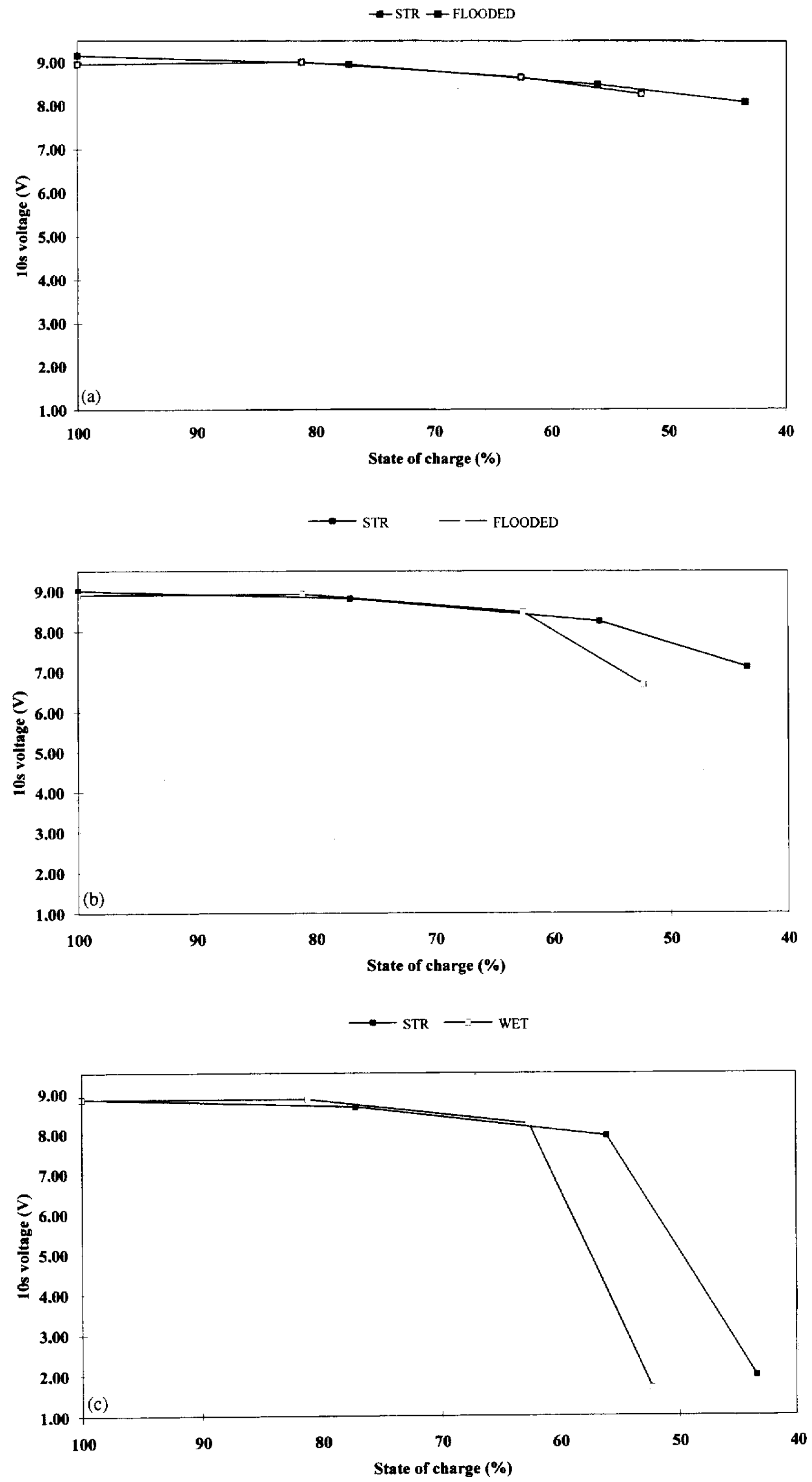

Fig. 4. (a) 10 s voltage at the cold-cranking test at different states-of-charge, first discharge. (b) 10 s voltage in cold-cranking test at different states-of-charge, second discharge. (c) 10 s voltage in cold-cranking test at different states-of-charge, third discharge.

Table 2
Dimensions, weight and performance of the STR range of batteries

Battery type	L1	L2	L3	L5
Dimensions				
Length (mm)	207	242	278	353
Width (mm)	175	175	175	175
Heigth (mm)	190	190	190	190
Weight (kg)	13.1	15.4	17.7	22.9
Capacity ($C_{20}/20$) (Ah)	45	55	65	85
Reserve capacity (min)	75	95	115	155
Cold-cranking amps (A)				
EN 60095-1 (7.5 V–10 s/ 6 V–90 s) (A)	450	540	640	720
IEC (8.4 V–60 s) (A)	260	320	400	450

Table 3
Initial state-of-charge of both types of batteries before the cold-cranking test

State-of-charge	I	II	III
Flooded (%)	80	60	50
STR (%)	75	55	45

each cycle for the same capacity discharged (i.e., for a lower state-of-charge with the STR batteries) are nearly the same for both types of batteries.

3.2.2. *After long storage*

The following two methods were used to study the cold-cranking ability of the batteries after a long period of storage.

3.2.2.1. Open-circuit storage on a partially discharged battery. A comparative test between flooded (hybrid and all-calcium) and STR batteries was carried out after a definite period of storage on L1-type batteries that were already partially discharged. The batteries were first discharged at a low rate to reach 60% state-of-charge. They were then stored at 20 °C for three months. These test conditions were intended to represent the actual storage conditions in some OE applications. At the end of this period, a cold-cranking test was performed without any recharge. The results (Table 4) show that the STR battery, due to its low self-discharge (similar to that of a flooded lead–calcium battery), displays good cold-cranking after a period of three months of open-circuit storage at 20 °C in a partially discharged state.

3.2.2.2. Open-circuit storage on a fully charged battery. Due to its low self-discharge, the STR battery has a good ability to be stored at open-circuit for long periods before being recharged. Fig. 5 presents the evolution of the open-circuit voltage during storage directly after the formation process. The open-circuit voltage and the performance at the end of the storage period, before and after recharge, are given in Table 5. These results show that the STR battery is still able to start an engine in usual conditions after 16 months of storage.

3.3. *Rechargeability after a deep discharge*

The purpose of this test is to evaluate the behaviour of a STR battery when the discharged battery is recharged after jump starting the car. The batteries tested were the STR L1 250A (IEC) and L3 400A (IEC) types. The batteries were discharged completely, connected to a 10 Ω resistance for seven days, and then recharged at ambient temperature with a constant voltage of 13.5 V for 3 h. The maximum current was 30 A. These test conditions were determined by a previous test on a vehicle.

Table 4
Cold-cranking ability after three months of open-circuit storage at 20 °C for a partially discharged battery (60% state-of-charge), L1 250A (IEC)

Battery type	STR	Flooded Pb–Ca	Flooded hybrid
Initial performance ($C_{20}/20$ capacity) (Ah)	46	53	51
Cold-cranking at − 18 °C			
Voltage after 10 s (V)	9.26	9.29	9.35
Voltage after 30 s (V)	9.11	9.14	9.17
Voltage after 60 s (V)	8.88	8.93	8.90
Time to 7.2 V (s)	120	126	136
Time to 6 V (s)	126	135	143
Discharge to 60% state-of-charge and open-circuit storage at 20°C for 3 months			
Cold-cranking at − 18 °C			
Voltage after 10 s (V)	8.85	8.9	8.2
Voltage after 30 s (V)	7.88	8.53	
Voltage after 60 s (V)			
Time to 7.2 V (s)	32	37	23
Time to 6 V (s)	35	39	25
Residual capacity	22.9	27.5	18.2
Discharge capacity (% of the initial capacity)	95	97	79

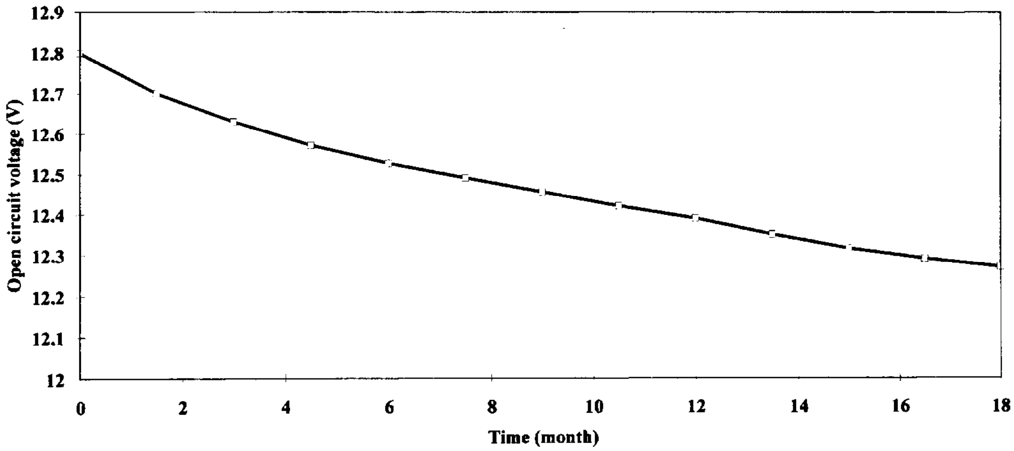

Fig. 5. Open-circuit voltage vs. time at 20 °C.

The current of the battery was recorded (Fig. 6). After 3 h of charge, the battery was discharged at the 20 h rate, and the restored capacity was measured. The results are presented in Table 6 and show that the STR rechargeability after a deep-discharge test is good. The level of the restored capacity depends on the battery size.

3.4. *Life test*

3.4.1. *Overcharge / storage test*

This life test was performed to compare the behaviour and the life of the two technologies (flooded and VRLA) under conditions of temperature and overcharge that are representative of severe use in cars, such as taxis. The batteries tested were the L3 type, 15 plates: (i) flooded, all-calcium, rolled expanded metal grids, and (ii) STR.

The batteries were submitted to successive schedules:

1. 1 week of open-circuit storage at constant temperature;
2. 1 week of overcharge at constant voltage and constant temperature;
3. 1 week of open-circuit storage at constant temperature;
4. 1 week of overcharge at constant voltage and constant temperature;
5. a cold-cranking test, and
6. a $C_{20}/20$ discharge test.

During the whole test, the electrolyte level was maintained in the flooded batteries. The influence of parameters such as temperature, voltage and time of storage on the degradation of battery performance was studied. The values of the parameters are given in Table 7.

During this test, the evolution of the following features was followed, an example of each one is presented in Fig. 7 for an overcharge voltage of 14 V:

1. overcharge current at the end of the overcharge period, Fig. 7(a);
2. weight loss during the overcharge period, Fig. 7(b);
3. 10 s voltage during the cold-cranking test, Fig. 7(c);
4. duration at 7.2 V during the cold-cranking test, Fig. 7(d), and
5. 20 h rate capacity, Fig. 7(e).

The results are summarized in Table 7. It appears that the life of the STR batteries is roughly the same as that of

Table 5
Mean values of cold-cranking ability of STR batteries after 16 months of open-circuit storage at 20 °C

Battery type	L1	L2	YL3
Open-circuit voltage (V)	12.22	12.35	12.28
Cold-cranking at − 18° C			
Voltage after 10 s (V)	8.27	8.44	8.33
Voltage after 30 s (V)	7.03	6.88	6.7
Voltage after 60 s (V)			
Time to 7.2 V (s)	26	28	26
Time to 6 V (s)	28	34	29
Complete recharge			
$C_{20}/20$ discharge (Ah)	46.6	55	66
Cold-cranking at − 18°C			
Voltage after 10 s (V)	9.23	9.22	9.15
Voltage after 30 s (V)	9.05	9	8.96
Voltage after 60 s (V)	8.76	8.7	8.56
Time to 7.2 V (s)	107	99	103
Time to 6 V (s)	118	113	116

Table 6
Rechargeability of L1 and L3 STR batteries after discharge through a 10 Ω resistance for seven days

Battery type	STR L1 250A (IEC)	STR L3 400A (IEC)
Initial $C_{20}/20$ capacity (Ah)	46.1	65.4
Ah absorbed after 3 h of charge (Ah)	48	57.2
Maximum current (A)	30	30
Time to reach maximum current (min)	49	35
Capacity restored ($C_{20}/20$ rate) (Ah)	27	31.5
$C_{20}/20$ restored/ $C_{20}/20$ accepted (%)	56	46
$C_{20}/20$ restored/ $C_{20}/20$ initial (%)	59	48

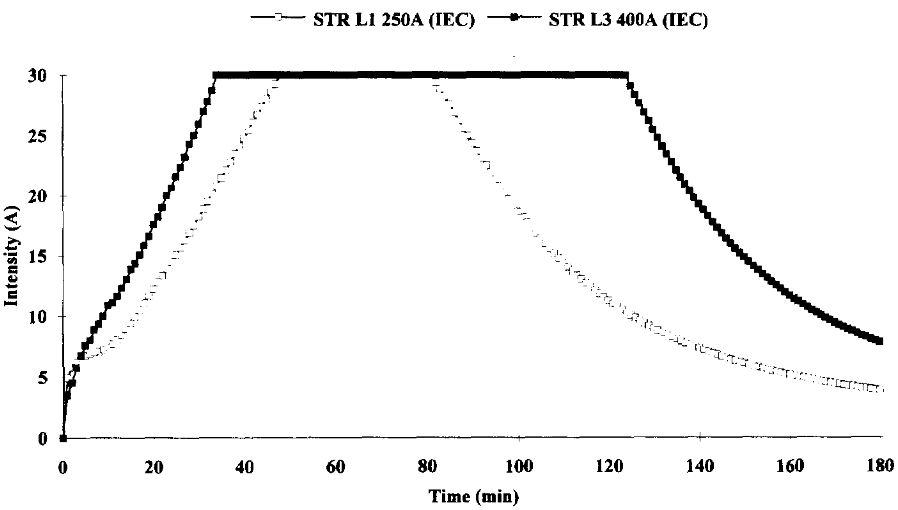

Fig. 6. Charging current vs. time after a deep-discharge test.

flooded all-calcium batteries. For the same life, the capacity is maintained at a higher level with the STR battery than with the flooded counterpart. Moreover, the weight loss is about four times lower with the STR battery.

The contribution of the different parameters to the degradation of the battery performance has been analyzed by means of variance analysis. The results are given in Table 8 and reveal that the level of contribution of the different parameters is nearly the same for both technologies in terms of battery performance, but is different with respect to overcharge current and the weight loss:

1. temperature is the most influential parameter on the cold-cranking performance;
2. time of storage is the second most influential parameter, but the most important with regards the evolution of the capacity;
3. the voltage appears to have a higher influence on weight loss and overcharge current in the VRLA than in the flooded technology.

3.4.2. Cycling test

This test was conducted in order to compare the behaviour of the two technologies (flooded and VRLA) during cycling at 25% depth-of-discharge. The test conditions were those used in the endurance test of the European Standard *EN 60095-1* that includes a control of the cold-cranking performance and a $C_{20}/20$ discharge of each unit. The batteries tested were L3 type, 15 plates (with the same plates for both technologies): (i) flooded all-calcium, rolled/expanded metal grids, 70 Ah, 400 A (IEC), and (ii) STR, 65 Ah, 400 A (IEC).

The batteries were submitted to the following successive schedules:

1. 32 cycles at 40 °C, each cycle being constituted by: (i) discharge for 1 h at $I = 5In$; (ii) charge for 2 h at 14.8 V; maximum current limited to $10In$;
2. 72 h of open-circuit storage at 40 °C;
3. cold-cranking test at − 18 °C and 400 A, and
4. $C_{20}/20$ discharge test.

The complete charge was made according to the *EN 60095-1* test.

The total number of schedules achieved until the voltage, after 30 s of cold-cranking discharge was less than 7.2 V, was 12 schedules for the STR battery and 8 for the all-calcium flooded one, see Fig. 8(a). This improvement can be explained by the compression on the group that

Table 7
Life of flooded Pb–Ca and STR batteries for different conditions of temperature and voltage

Temperature	Voltage	Flooded Pb-Ca		STR	
		Number of schedules	Total time (overcharge + storage)	Number of schedules	Total time (overcharge + storage)
(°C)	(V)		(h)		(h)
40	14	14	9408	13	8736
40	14.8	15	10080	14	9408
60	14	4	2688	5	3360
60	14.8	5	3360	4	2688

maintains a higher adherence of the active mass to the grid than in the flooded battery. The phenomenon can also be observed in the evolution of the $C_{20}/20$ capacity (Fig. 8(b)); the capacity is maintained at a higher level for the STR battery than for the flooded unit.

3.5. Vibration test

STR batteries have been tested according to the different levels of vibration that are specified in the European *EN 60095-1* test. The good behaviour of the STR batteries, which is at the level of the highest requirements for truck batteries, is due mainly to the compression of the group inside the cell (Table 9).

3.6. Field test

In order to validate the concept of using VRLA technology for automotive applications, 42 taxis were equipped with STR batteries in Paris (Mercedes Peugeot), in Milano (Fiat, Ford, Opel, Peugeot, Volvo), and in Geneva (Mercedes). The batteries tested were L3 type, 400 A (IEC) 65 Ah. For the whole field test, the distances

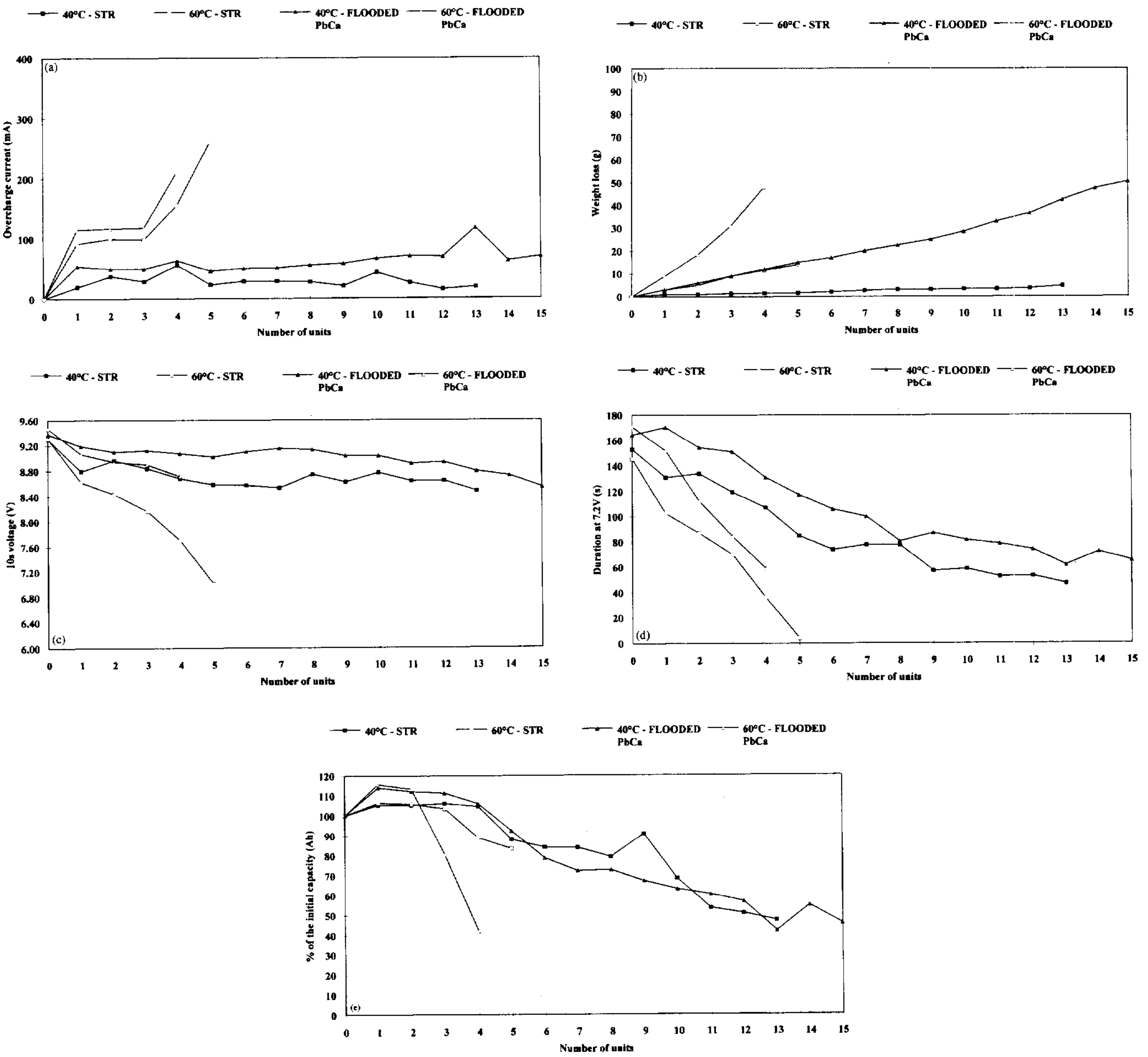

Fig. 7. (a) Overcharge current at end of overcharge/storage test at 14 V. (b) Cumulative weight loss per cell during overcharge/storage test at 14 V. (c) 10 s voltage on cold-cranking test after overcharge/storage test at 14 V. (d) Time to 7.2 V on cold-cranking test after overcharge/storage test at 14 V. (e) $C_{20}/20$ capacity after overcharge/storage test at 14 V.

Table 8
Level of contribution of temperature, voltage and time on the performance of flooded and STR batteries [a]

A	B	C		Flooded Pb–Ca					STR				
				$C_{20}/20$	U 10 [b]	t 7.2 V [c]	I	dp	$C_{20}/20$	U 10	t 7.2 V	I	dp
14–14.8	40–60	1–2–4	A	13 [d]	50 [d]	42 [d]	75 [d]	31 [d]	1	36 [d]	45 [d]	31	42 [d]
			B		3	2	3	6	5			25	19 [d]
			C	51 [d]	35 [d]	49 [d]	10	42 [d]	44	44 [d]	44 [d]	8	16
			AB		1	1		1	12	2	1	7	10
			AC	35 [d]	9	7 [d]	9	17 [d]	3	12	5 [d]	16	10
			BC		2		3	2	12	6	4 [d]	8	3
14–14.8	40	1–6–12	B		3	1	77 [d]	14		21	1	40	38
			C	100 [d]	89	98 [d]	19	78	98 [d]	54	95 [d]	30	40
			BC										

[a] A: temperature; B: voltage; C: time (number of schedules); AB: interaction temperature × voltage; BC: interaction voltage × time; AC interaction temperature × time.

[b] Voltage after 10 s.

[c] Time to 7.2 V.

[d] Significant parameter.

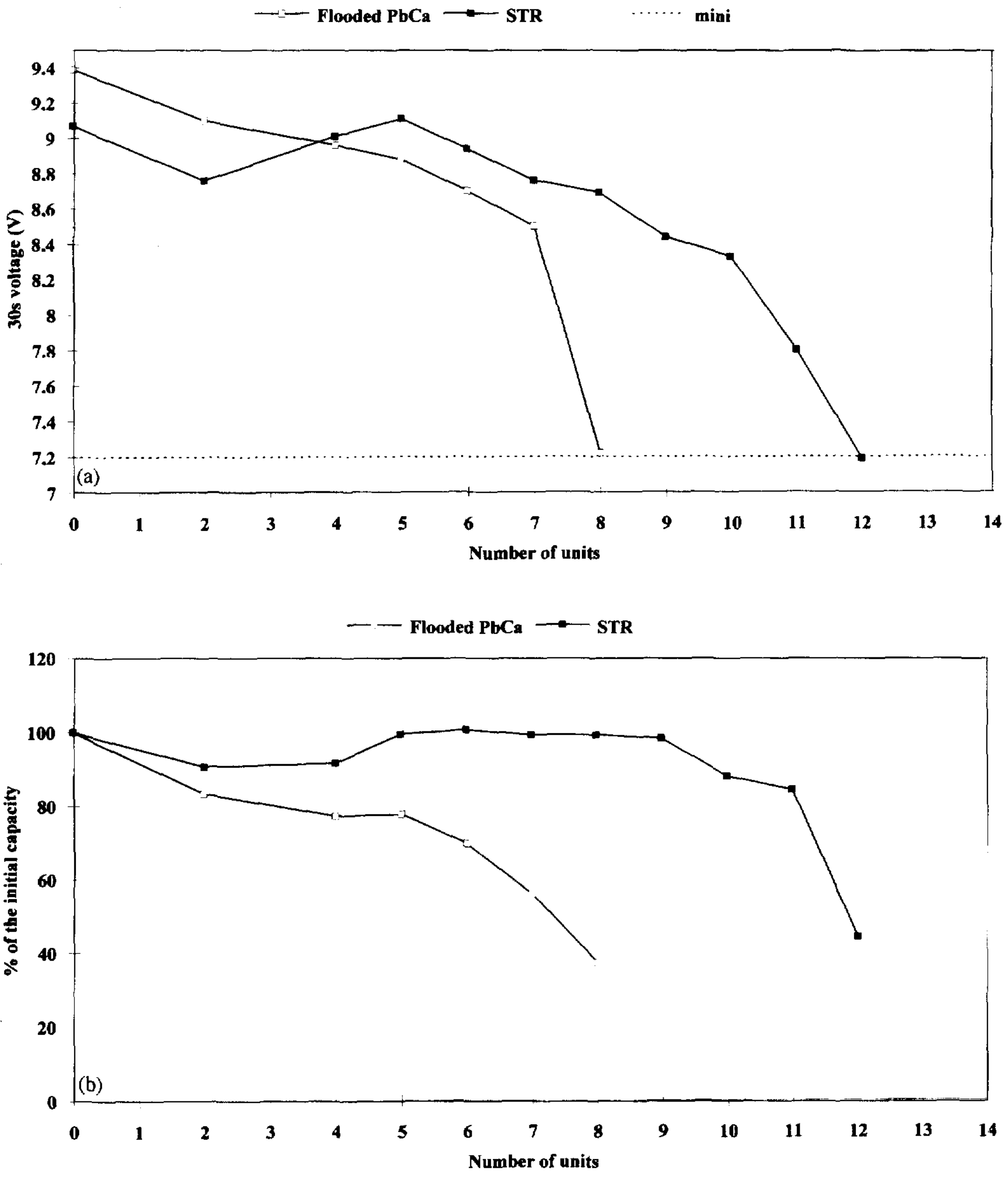

Fig. 8. (a) 30 s voltage on cold-cranking test after cycling test at 25% depth-of-discharge. (b) $C_{20}/20$ capacity after cycling test at 25% depth-of-discharge.

Table 9
Mean values of the duration of high-rate discharge after tests made at different levels of vibration

Requirement	1	2	3
Minimum width of battery cover/case to be covered (mm)	15	33	33
Period of vibration (h)	2	2	20
Maximum acceleration on the battery (m s^{-2})	30	60	60
Discharge at 25 °C at 0.6 Icc duration at 7.2 V			
Specification (s)	> 60	> 60	> 60
Result (s)	234	226	235

covered by the vehicles before failure and without any incident were between 52 000 and 183 000 km, during an average period of 23 months. From experience in such field conditions, it can be concluded that this life is more or less 50% higher than that obtained for flooded batteries.

In Paris, where the average distance covered before failure was 131 000 km for 21 months, some of the batteries were tested every six months. The results showed that after 12 months, the $C_{20}/20$ capacity was still equal to 100% of the initial value, and 55% after 25 months of testing.

The battery analysis did not reveal any failure due to a defect of the valves. The weight loss measured was relatively low (about 20 g/cell). No container deformation was observed. The positive active-mass was generally muddy and the positive grid corroded. The negative mass exhibited a slight shrinkage.

4. Safety study

This study has been carried out in order to validate the possible fitting of the STR battery inside the passenger compartment. Today, most of the batteries that are installed inside the passenger compartment or in the trunk are flooded batteries with a central gassing system. The target was to compare this system with the STR technology and with the traditional flooded battery (normal vent plugs) with respect to safety behaviour.

After having identified the different risks related to the environment of the battery in the car and to a misuse of the system, it appears that the major risks are due to:

1. charging circuit on the vehicle;
2. damage caused by the battery after an accident, and
3. maintenance or assembly operations.

In this last case, the risks are mainly due to electrolyte leakage that occurs during or after maintenance operations, i.e., if the plugs are not correctly screwed, if the tube has not been well positioned, or if the battery has to be tilted during the vehicle assembly. Thus, tests were performed to represent as much as possible the different conditions of running in a battery-degrading mode, in order to compare the behaviour of the different types of batteries.

4.1. Overcharge at the maximum current of the alternator

The batteries were submitted to a constant current corresponding to 1.5 × *Cn* for 2 h. During this overcharge, the temperature was monitored both inside the battery and at the container wall. The results are presented in Table 10 and show that the temperature increases at the same rate for the different types of battery. During this period, gas emisssion is observed with VRLA technology. With flooded batteries, gas emission is accompanied by electrolyte leakage, either through the tube with a central gassing system or through the vent covers with a traditional unit. The test does not show a specific failure mode for the VRLA technology, but an advantage in terms of safety due to the absence of leakage.

4.2. Short-circuit test

This test was made by connecting the positive and negative terminals with a short-circuit resistance of 0.55

Table 10
Comparative study of degrading mode between STR and flooded batteries with a central gassing system and with vent covers

Tests	STR	Flooded battery with a central gassing system	Flooded battery with vent covers
Overcharge at the maximum current of the alternator Constant current: 1.5 × *Cn* First step: after 40 min	Battery voltage: 19 V $\Delta T = 2$ °C/min Significant gas emission with some acid particles No external damage of the battery	Battery voltage: 18 V $\Delta T = 2$ °C/min Electrolyte leakage only by the tube after 5 min of test No external damage of the battery	Battery voltage: 18 V $\Delta T = 2$ °C/min Electrolyte leakage by the vent covers No external damage of the battery
Short-circuit			
Maximum current (A)	4 × *Icc*	3.5 × *Icc*	4 × *Icc*
Test duration (s)	8–9	3-4	9–15
Thermal runaway (overcharge 14.8 V, 80 °C, 7h, 10 A maximum)	No signs of thermal runaway	No signs of thermal runaway	
Complete reversal after an overcharge period	No leakage after a few hours	Filling of the tube Leakage by the tube after returning to vertical position	Immediate leakage

mΩ. The maximum current recorded is roughly the same for the different batteries (see Table 10). The failure mode due to the fusion of the negative terminal is not specific to VRLA technology.

4.3. Thermal runaway

Fully-charged batteries were placed in an oven at 80 °C for 16 h. Then, the batteries were submitted to an overcharge test at 14.8 V for 7 h. The temperature was maintained at 80 °C. The recorded current for each battery is given in Table 10 and does not reveal any sign of thermal runaway under these test conditions.

4.4. Complete reversal after an overcharge period

Fully-charged batteries were submitted to an overcharge test at ambient temperature for 24 h at 14.8 V. Immediately after the overcharge period, the battery was disconnected from the circuit and turned upside down. After 24 h in this position, the STR battery did not display any trace of acid on the lid or around the valves. After a few minutes in this position, the flooded battery with a central gassing system shows filling of the tube by electrolyte which is spilt when the battery is returned in its initial position. The up-turning of the flooded battery with vent covers leads immediately to electrolyte leakage (Table 10). This situation pertains to flooded batteries with standard covers and without any system for retention of the electrolyte. The behaviour could be different with batteries having, for example, a double cover.

5. Conclusions

As previously described, the STR technology leads to a product with the following characteristics:

1. absolutely no maintenance: totally maintenance-free;
2. many possibilities for fitting in the car and especially appropriate for placing inside the passenger compartment or in the trunk;
3. good aptitude to maintain its initial capacity at a high level during the battery life;
4. good cycling ability;
5. cranking power and reserve capacity similar to a comparable flooded battery in terms of lead weight;
6. good charge-acceptance and good rechargeability, and
7. good open-circuit storage compared with hybrid technology.

Moreover, the STR technology enables batteries to be designed to comply with the 'original equipment' specifications and to design products for the different European replacement markets.

Due to the technical choices made for the components (expanded metal grids, separator with a good mechanical strength and sealable, plastic parts in polypropylene) and for the manufacturing process, this battery is manufactured today on a production line that is very similar to that for a flooded battery. There is a good level of productivity and the reliability is the same as that found with the best flooded batteries. For all these reasons, the STR battery is produced at a cost that is acceptable for automotive applications. The first mass production of the STR battery started in the middle of 1994 and it has been commercialized in Europe since September 1994. The range is actually composed of four sizes of container, namely, L1, L2, L3, L5. The delivery of the STR battery for 'original equipment' applications has commenced.

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