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# VALVE REGULATED LEAD ACID BATTERIES (VRLAB) FOR AUTOMOTIVE APPLICATION

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**Among the various types of lead-acid batteries manufactured throughout the world, the automotive or the SLI (Starting, Lighting & Ignition) type far exceeds the other types in terms of number and production value. This is due to the constantly increasing production of automobiles and the regular replacements required for such batteries every 3-4 years. Flooded lead-acid batteries have long been used for starter applications but because of the difficulties connected with handling of such batteries and also due to the development of valve-regulated lead-acid batteries which offer good performance characteristics like instant start even after a prolonged period of disuse, absence of leakage of the corrosive acid electrolyte and no necessity of topping up with distilled water have encouraged designers to propose VRLA battery for automotive application in recent years. The development of VR SLI batteries and field trials with these batteries carried out by some manufacturers are discussed in this paper along with the details of special characteristics of the various components used and the test results as per various specifications like JIS, DIN, SAE and PSA - BSESA.**

**Keywords: Lead Acid Battery, Automotive application, Valve Regulated type**

## INTRODUCTION

Among the various types of lead-acid battery manufactured throughout the world, the automotive or the SLI (Starting, Lighting & Ignition) type far exceeds the other types in terms of number and production value. This is due to the constantly increasing production of automobiles and the regular replacements required for such batteries every 3-4 years.

The purpose of the SLI battery is

i) to start the engine in all weather conditions and

ii) to ensure operation in the event of failure of the onboard electrical recharging system so that the auxiliary electrical equipments operate smoothly for a certain period.

Flooded lead-acid batteries have long been used for starter applications but because of the difficulties connected with handling of such batteries and also due to the development of valve-regulated lead-acid batteries which offer good performance characteristics like instant start even after a prolonged idle period, absence of leakage of the corrosive acid electrolyte and no necessity of topping up with distilled water have encouraged designers to propose VRLA battery for automotive application in recent years.

### Field trials with automotive VRLA batteries

A few companies have reported the results of successful trials with VR automotive batteries produced with absorptive separator technology. They are:

1. Chloride Technical Ltd, UK [1,2]
2. Japan Storage Battery Co. Ltd., Kyoto, Japan [3]
3. FIAMM, Montecchio Maggiore, Italy [4]
4. Matsushita Battery Ind. Co. Ltd., Osaka, Japan [5,6,7]
5. Yuasa Corporation, Kanagawa, Japan [8]
6. Seagull, China [9]
7. Johnson Controls Battery group Inc., Milwaukee, WI, USA [10 ]
8. Sonnenschein, Budingen, Germany [11]
9. Varta, Germany [12]

Following extensive field trials and bench tests, Chloride Technical Ltd, started production of such batteries in Australia in April 1981 [1]. These batteries (Torque Starter) have a restricted common gas passage and give lives and warranty claims comparable with conventional flooded low-maintenance automotive batteries [2]. Japan Storage Batteries Co. and FIAMM have conducted successful trials for 2 years with VRLA battery on automotives and are satisfied with their performance except that these batteries exhibit reduced low-rate capacity and that a little improvement is required in the life of the batteries under higher temperatures. The Matsushita VRLA battery for automotive application (of which seven models are available) has undergone tremendous improvements in the life at higher temperature and recovery after deep-discharge and long standing.

For SLI applications, motorcycle (MC) VRLA battery has achieved successful growth since Yuasa introduced dry-charged (unfilled) VRLA batteries in 1983 [8]. In early 1980's, scooters with 50 ml engines and 3 Ah capacity batteries were becoming popular in Japan and buggy-type MC's with 10 Ah batteries were rapidly becoming popular in the USA. VRLA batteries have been installed in large MC's of upto 1200 cc engines and even in watercrafts. Nowadays, 70% of new MC's are equipped with VRLA batteries. Since the performance and cycle life of the batteries depend largely on the accuracy of the acid volume poured into the cells, great efforts have been made to improve the acid bottle and filling system. At present, a 'push in' system is used. This allows easy and accurate acid fill to each cell and, consequently, decreases significantly the probability of misfilling.

Automotive VRLA batteries were also developed in early 1980's, but their usage has not grown appreciably. In 1989, Mazda adopted VRLA batteries for its sports cars. Recently, Nissan used the technology in a passenger car for which good maneuverability is one of the selling points. In Japan, VRLA batteries for agricultural machinery have been developed since 1987 following the success of MC application.

Johnson Controls Inc., have developed an AGM based VRLA battery for SLI application [10]. They have tested their batteries in taxicab fleet vehicles with unmodified voltage regulator system, and the results show that these batteries give 36% more mileage compared with conventional flooded hybrid batteries. When tested according to SAE J 240 specification, but at 348K, the batteries were able to deliver 38% more cycles.

**TABLE I: Automotive VRLA batteries**

| | Torque starter [1] | Japan storage battery CO [3] | FIAMM [4] | Matsushita Bty Co [5] | Yuasa [8] | Guangzhou [9] |
|---|---|---|---|---|---|---|
| 1. $C_{20}$ ($C_5$) | a) 47 | 34.4 (28.6)* | 53 (L2) | 38.3 (32)* | 34 (28)* | 60 |
| (Ah) | b) --- | --- | 60 (L3) | 55.1 (46)* | --- | 60 |
| 2. $C_r$ (min) | a) 80 | 50** | 95 | 56 | 50** | 105 |
| | b) --- | --- | 120 | 85 | --- | 103 |
| 3. Dimensions | a) 238x175x175 | 195 x 127 x 227 | 242 x 175 x 175 | 238 x 128 x 187 | 127 x 195 x 190 | 247x173x224 |
| (mm) | b) --- | --- | 278 x 175 x 175 | 222 x 173 x 226 | --- | --- |
| 4. Weight | a) 14.1 | 10.2 | 16.5 | 9.7 | 10.0 | 18.30 |
| (kg) | b) --- | --- | 18.6 | 13.8 | --- | 18.50 |
| 5. Sp energy | a) 40 (33.65) | 41.2 | 38.5 | 47.4** (39.6) | 40.8 (33.6) | 39.34 |
| $Wh_{20}$/kg ($Wh_5$/kg) | b) --- | | 38.7 | 47.9** (40.0) | --- | 38.79 |
| 6. Weight per | a) 0.176 | 0.204 | 0.173 | 0.173 | 0.2 | 0.174 |
| min of RC (kg) | b) --- | --- | 0.155 | 0.162 | --- | 0.180 |
| 7. CCA at 255 K | a) 450 | --- | 400 | 350 | 370*** | **** |
| (A) | b) --- | --- | 450 | 450 | | |
| 8. Charge acceptance (A) | a) 13.1 | 13.0 | | | | |
| 9. Grid alloy | +Pb-Ca-Sn Cast? | Pb-Ca-Sn Cast? | Pb-Ca-Sn Cast? | Pb-Ca-Sn (Expd) | Pb-Ca-Sn | Pb-Ca-Sn |
| | -Pb-Ca-Sn Cast? | Pb-Ca-Sn Cast? | Pb-Ca-Sn Cast? | Pb-Ca-Sn (Expd) | Pb-Ca-Sn | Pb 0.6% Sb |
| 10. Separator | Conv. AGM | Conv. AGM | Conv. AGM | AGM + Polyester + Inorg. Powder | Con. AGM | Conv. AGM |
| 11. Container | PP | Reinf. PP | PP–$CaCO_3$ or talc | PP | PP | PP + talc |
| 12. Valve | Cap type | Cap type | Cap type | Flat rubber sheet | Cap type | Cap type |

* Computed values ** Computed values *** 150 A at 258 K:5s voltage = 10.4 V; duration 3.9 minutes

**** (a) $9C_{20}$ A at 258 K:5s voltage = 9.1 V; 30 s voltage = 8.78 V

(b) $9C_{20}$ A at 258 K:5s voltage = 9.02 V; 30 s voltage = 8.77 V

The performance characteristics and constructional features of these batteries are given in Table I. One striking feature of these batteries is that all of them use an alloy of Pb-Ca-Sn for both positive and negative grids.

**Alloys for grids**

The Matsushita Company employs a special technique for preparing the expanded grids in order to improve the poor recovery after over-discharge [5]. A special alloy of Pb-5%Sn alloy is clad over the normal Pb-Ca-Sn alloy before the sheet is sent for expanding. However, for more severe over-discharge, the tin content of the base alloy as well as that of the surface sheet has been increased [6,7].

Guangzhou Storage Battery Enterprises Co. Ltd. of China experimented [9] with VRLA batteries with 2 types of positive grid alloys: a) Pb-Ca-Sn with other proprietary components and b) Pb-0.6% Sb. The corrosion resistance of the latter alloy is inferior to that of the former alloy. At the end of life, the calcium batteries were found to have failed due to "dry-out" and some corrosion at the negative strap. The positive and negative plates were in good condition. However, the low antimony battery failed due to "dry-out" severe corrosion of positive grid and some corrosion at the negative strap. Hence the production low antimony VRLA SLI batteries was abandoned.

All the other manufacturers use lead-calcium-tin alloys for both the positive and negative grids. JCI use a 0.045% Ca-Pb alloy with silver addition. This was arrived at after testing with 0.065% calcium-lead alloy. Book-moulded radial grids both for positive and negatives are used.

**Reduction in positive grid corrosion**

Although VRLA batteries have better charge acceptance characteristics, they will tend to be overcharged [5]. Matsushita Co. has made innovations in the AGM separator used for their automotive VRLA batteries by including polyester fibres and inorganic powder [9]. This type of AGM is one of the reasons for the control of the gas-recombination reaction and thus the reduced overcharge current for the positive grid. The batteries developed by Matsushita exhibit the same behaviour as a flooded SLI battery during constant potential overcharge.

The resistance to decreased life during higher temperature (348 K) operation has been again due to the increased tin content of the positive grid alloy. Moreover, drying out of the electrolyte, which was thought possible at high temperature, was not experienced. Chinese manufacturers have included some proprietary components in the Pb-Ca-Sn alloy and claim superior life and good corrosion resistance.

**Flexibility in placement of batteries**

Advantages such as the flexibility of being able to install the battery elsewhere than the engine compartment have been appreciated in actual use [5]. Batteries designed specially for original equipment have been installed in the luggage

**TABLE II: CCA performance - L2 and L3 VRLA batteries (FIAMM) [4]**

| Test type | L2 | DIN | L3 | SAE L2 | SAE L3 | Eurobat L2 | Eurobat L3 | Chin Natl Std GB 5008-1-91 |
|---|---|---|---|---|---|---|---|---|
| CCA (A) (255 K) | 340 | | 380 | 670 | 720 | 700 | 750 | $9C_{20}$ (258 K) |
| Torque starter | | | | | | | | |
| | CCA | (A) | Time(s) | 5s voltage | | Mean V(V) | Ah output | |
| at 266 K | | 250 | 151 | 10.02 | | 9.34 | 15.07 | |
| at 255 K) | | 250 | 151 | 9.58 | | 8.92 | 10.49 | |
| | | 350 | 77 | 8.80 | | 8.65 | 7.49 | |
| | | 400 | 62 | 8.65 | | 7.74 | 6.03 | |
| | | 450 | 32 | 8.11 | | 7.27 | 4.00 | |

Japan Storage Battery Co.
150 A at 288 K for 2.9 minutes with 5s voltage of 9.75 V

Matsushita
at 255 K CCA is 350 and 450 A, respectively for batteries with $C_5$ = 32 and 38 Ah

Guangzhaou

540 A
$V_{5s}$ (V)=9.10
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| | CCA | (A) | Time(s) | 5s voltage | | Mean V(V) | Ah output | |
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| | | 350 | 77 | 8.80 | | 8.65 | 7.49 | |
| | | 400 | 62 | 8.65 | | 7.74 | 6.03 | |
| | | 450 | 32 | 8.11 | | 7.27 | 4.00 | |
| Japan Storage Battery Co. 150 A at 288 K for 2.9 minutes with 5s voltage of 9.75 V | | | | | | | | |
| Matsushita at 255 K CCA is 350 and 450 A, respectively for batteries with $C_5$ = 32 and 38 Ah | | | | | | | | |
| Guangzhaou | | | | | | | | 540 A $V_{5s}$ (V)=9.10 $V_{30s}$(V)=8.78 |

compartment of cars or at another place away from the engine compartment.

### Safety aspects

Japan Storage Battery Co. has tested their batteries for explosion-proof nature during continuous overcharge at currents varying from 2 to 20 Å. No explosion occurred in the case of VRLAB, but with flooded design there were explosions when the batteries were charged at 4 Å and higher currents. When tested in various positions, there is no leakage of electrolyte from VRLAB.

### Testing of VRLA automotive batteries

Batteries of the VRLA type have been successfully tested as per SAE, PSDA-BSESA, DIN, New Eurobat JIS and GB 5008-1-91 specifications by several authors and have been found to pass or exceed the performance limits.

### Electrical characteristics

The electrical characteristics like low rate and high rate capacities, recombination efficiencies, water loss, charge acceptance, life tests, internal resistance and self-discharge are discussed below.

**TABLE III: Water loss (WL) and recombination efficiency (RE)**

| Torque starter | WL (g) Weeks of Overcharge 1st | 2nd | 4th | 6th | 8th | 9th | 12th |
|---|---|---|---|---|---|---|---|
| CP @ 14.5V* | negli | 6 | 9 | 11 | 12 | 13 | --- |
| CC @ 2.0A | 36 | 72 | 120 | 156 | 168 | --- | --- |
| Faradaic Loss on Battery without recombination | | | | | | | |
| CP @ 14.5V | 96 | 168 | 312 | 444 | 553 | --- | --- |
| CC @ 2.0A | 677 | 1354 | 2708 | 4062 | 5416 | --- | --- |
| FIAMM | | | | | | | |
| 4 to 77g WL per battry after 12 months' field trials | | | | | | | |
| CP @ 14.4 V 313 K 14(3 weeks) 17.5(6 weeks) 22g (12th) E > 99% | | | | | | | |
| Japan Storte Battery Co | | | | | | | |
| 0 to 35 g (average 20 g) WL after 50,000 Km trials | | | | | | | |
| 100% RE upto 0.05 C A Charging current | | | | | | | |
| Matsushita Battery Co | | | | | | | |
| No "dry-out" even at 348 K endurance test | | | | | | | |
| Guangzhou Storage Battery Enterprises Co Ltd | | | | | | | |
| Seagull (a) 0.01 g/Ah (Pb-Ca-Al + others) | | | | | | | |
| (b) 0.15 g/Ah (Pb-0.6% Sb) | | | | | | | |

* No weight loss (100% RE) at 14.1 V CP at 298 K charge upto 6000 hours

+ On a battery which had been on open circuit for 18 months

### Low rate and high rate capacities

As mentioned earlier, the low rate capacity is lower for VRLA battery, while for the same size and weight, the cold cranking amperes (CCA) is very much improved as seen from Table II. Under the starting conditions of high current and low temperature, ohmic losses are appreciable and the low internal resistance of VRLA battery provides high initial current. The initial voltage is higher by 1V and it can deliver 10% higher wattage output than a comparable flooded design.

### Recombination efficiency and water losses

The details of water loss and recombination efficiency (RE) are given in Table III. When charged at voltage levels less than 14.5 V for a 12 V battery, the water loss is highly negligible compared with faradaic losses (i.e., losses on equivalent batteries without recombination, which theoretically is 0.336 g per cell per Ah).

Under normal constant potential (CP) charge at 14.0 to 14.5 V for a 12 V battery, the RE is 96-100%, and under abuse conditions it reduces to less than 90%.

### Charge acceptance tests

All the batteries accept charge in a better manner than the flooded maintenance-free batteries. The details are given in Table IV. The batteries are capable of recombining 100% upto a charging rate of 0.05 C A and at higher current rates the RE reduces.

### Endurance test (Life test)

The endurance characteristics of the batteries were tested by the manufacturers as per the SAE, modified SAE, PSA BSESA and DIN procedures and results are indicated in Table V.

**TABLE IV: Charge acceptance (BCI, SAE J 537)**

**Test:** Discharging at 25 A for 80% of $C_\tau$ followed by cooling to 273 K overnight and charging at 14.4 V CP at 273 K

**Requirement:** At the 10th minute the charging current should be a minimum of 2% of CCA

**Torque Starter:** 13.1 A mean value of 6 samples (SD 2.4) against a requirement of 8.4 A

**FIAMM:** 15 A against a requirement of 9 A

**Japan Storage Battery Co**

Even after the battery is left fully discharged for 12 days by connecting to a 10 W lamp and then left on open circuit for 15 days, it is capable of being charged. 13 A charge acceptance

**Matsushita**

Even after a over-discharge for about a month when an interior light is left switched on, the battery is able to pick up charge

**Internal resistance**

Because of the AGM separator, the internal resistance of these batteries is very low. Its value is 5 milli-ohm as compared with a value of 6.5 milli-ohm for an equivalent flooded battery.

**Self discharge rate**

Even after a period of 12-18 months idle period, the batteries are capable of cranking the engines.

**Merits and demerits of VRLA battery for SLI application**

The VRLA SLI battery technology is in an evolutionary stage. Successful trials have been conducted on VRLA battery for automotive application and such batteries are being slowly introduced as OE.

The advantages of VRLA battery for automotive use can be summarized as follows:

1. Completely maintenance-free i.e., no necessity to top up throughout its life (install and forget battery).
2. Virtually no emission of acid fumes and no spillage and so can be installed anywhere in the vehicle in any position.
3. Reduced size (i.e., more compact)
4. Higher output during cold cranking test (due to low internal resistance)
5. Longer life (because of better retention of positive active material)
6. Very low self-discharge
7. No explosion hazard
8. Can be transported in the bulk without any fear (as a non- hazardous cargo)
9. Requires less overcharge at room temperature and
10. Easy and quick installation for replacement batteries

The main shortcomings of the VRLA battery for SLI application are:

1. Reduced low-rate capacity
2. Increased cost (both due to materials and to the complexity of the processing). Automotive batteries are produced in huge quantities and therefore their cost is lower than that of an equivalent capacity VRLA battery for industrial or consumer use. The VRLA batteries are costlier because of special materials used and more complex manufacturing methods employed. Special materials are: newer alloys, absorptive micro-glass fibre separators and special components like container etc. The process is more complex because it involves stricter and more precisely controlled operations than those adopted for flooded batteries. With the use of special AGM separators which contain organic and inorganic materials and which have sufficient strength

**TABLE V: Endurance test**

| Test procedure | | Current (A) | Voltage (A) | Time (min) | Temp (K) | Requirements |
|---|---|---|---|---|---|---|
| J-240 SAE modified | Charge | 25 | 14.8 | 10 | 313 | After 70 times $C_{20}$ cycles |
| | Discharge | 25 | | 4 | | time of CCT to 7.2 V > 30 s |
| PSA-BSESA | Charge | 0.2 x $I_{cc}$ | 14.8 | 4 | 313 | 1 unit of CCT, 2160 cycles. |
| | Discharge | 0.03 x $I_{cc}$ | | 2 | | After 4 units, time to 7.2 V > 30s |
| DIN 43539 Part 2 | Charge | 5 x $I_{20}$ | 14.8 | 300 | 313 | 1 week cycling = 1 unit |
| | Discharge | 5 x $I_{20}$ | | 120 | | After 5 units, time f CCT to 7.2 V > 30 s |
| JIS Overcharge | Charge | 5 | --- | 300 | 313-318 | After each unit of 25 cycles |
| Life test D 5301 | Discharge | 20 | --- | 60 | | a discharge at 20 A |

Torque Starter : 7200 cycles at 313 K (SAE J 240) a) 1983 (5992 to 8132 cycles for 12 batteries)
as against a maximum of 4280 cycles for flooded designs
Cycling at 0.4 $C_{20}$ discharge for 1 h and charging at 0.1 $C_{20}$ for 5 h gave a life of 130-210 cycles

FIAMM : Exceeds the requirements as per SAE spec.
Easily exceeds the requirements as per PSA BSESA spec (> 4 units)
Largely exceeds the requirements as per DN spec. (> 4 units)

Japan St Bty Co : In the SAE test at 298 K the life is equal to a wet battery
In JIS tests the battery gives greater number of cycles
However, the life decreases sharply as the temperature increases

Matsushita : In the SAE-J240 test the sealed battery gives 5500 cycles against 4800 cycles shown by a flooded battery
in the JIS-D54301 test the VRLAB gives 150 cycles as against 10 cycles given by a flooded battery

Yuasa : 8000 cycles at 313 K (SAE J 240) for passing through an automatic high speed envelop/stacker machine, the cost can be greatly reduced [9].

3. Reduced shelf life (only two years as compared with a properly sealed dry-charged battery that have over five years of shelf life).

**Dual battery for automobiles**

In addition to the original functions, i.e. starting, lighting and ignition, the battery is now required to support increasing electrical and electronic functions, such as the engine control system, the maneuverable balance system, safety and security systems, and comfort and convenience equipment. At the same time, it has become rather difficult to provide the necessary space for the battery in the engine compartment. This is not only because of the increasing space required for the increasing amount of electrical/electronic equipment, but also because of the reduction in the hood height to give enhanced aerodynamic performance. Moreover, the battery must have a longer life, must be lighter, and must guarantee engine starting. In order to meet these requirements, a dual battery system has been proposed [13]. In this system, one battery handles the starting function and other fulfils the service function. VRLA technology is suitable for use in dual battery systems, provided appropriate conditions of charging voltage and environmental temperature are maintained. By virtue of its operational advantages, a VRLA battery will improve the electrical system and will lessen the weight of the car. Consequently, the demand for VRLA batteries in this application will increase.

The Thin Metal Foil (TMF$^{TM}$) battery [14-20] is an innovative patented VRLA design that is optimized for very high power applications. Bolder Technologies Corporation initially developed it for application in the power tool market, but its unprecedented power capability has made it a strong candidate for a number of other applications.

Johnson Controls has performed a variety of laboratory and field tests with 1.2 Ah cells to evaluate the TMF$^{TM}$ performance characteristics [10].

The most dramatic demonstration of performance to date has been the field test of a 12 V, 2.4 Ah pack of TMF$^{TM}$ cells that has been performing as the starting battery in a passenger vehicle (3.0 litre engine) in the Milwaukee, WI area for over seven months. The vehicle has accumulated over 31000 km during the test period. The 1.1 kg TMF$^{TM}$ pack directly replaced a conventional Group 65650 CCA SLI battery weighing almost 20 times more with no adjustment made to the vehicle charging system. For the first six weeks of the field test, the TMF$^{TM}$ battery was the sole battery in the vehicle. Cranking capability was demonstrated repeatedly at ambient temperatures as low as 244 K. After six weeks on test, a small VRLA BCI Group U2 battery was added as a reserve battery, with the TMF$^{TM}$ battery continuing to perform the starting function for the vehicle.

Of course, in auto-start applications the battery must support both the start and reserve functions. Due to its optimization for high power, the TMF$^{TM}$ design is not well suited for low-rate, reserve-type discharges. As in the Johnson Controls field test, the TMF$^{TM}$ battery can be coupled with a small conventional, flooded or AGM, lead/acid battery to form a dual battery system that supports both the start and reserve functions. The dual battery system maintains a dramatic weight and volume advantage over conventional automotive battery designs.

Table VI compares the performance and characteristics of a dual battery system designed to replace a Group 65 SLI battery. In addition, segregation of the two batteries with their specific functions facilitates further battery improvements. For example, advanced deep-discharge VRLA batteries, and eventually even emerging rechargeable lithium batteries, could ultimately become the reserve battery in the dual battery system.

Division of the start and reserve functions in a dual battery system also opens the door to a variety of other system advantages in addition to reduced weight and volume. Since the TMF$^{TM}$ start battery is decoupled from the reserve loads, it will remain charged during severe reserve loads, encountered for example when a vehicle dome light is left on or 'key-off' loads are supported during an extended vehicle stand period. Furthermore, the TMF$^{TM}$ start battery is sufficiently small to be removed readily from the engine compartment and relocated, for example in a wheel-well adjacent to the starter. The primary factors that have

**TABLE VI: TMF$^{TM}$ dual battery vs conventional automotive battery [10]**

| | TMF$^{TM}$ dual BCI | Conventional Group 65 |
|---|---|---|
| TMF$^{TM}$ battery | | |
| Weight (kg) | 2.6 | |
| Cranking power at 29C(kW) | 5 | |
| Capacity (Ah at C/20) | 5 | |
| Volume (L) | 1.2 | |
| Reserve battery | | |
| Weight (kg) | 11 | |
| Capacity (Ah at C/20) | 40 | |
| Volume (L) | 5.8 | |
| Combined batteries | | |
| Weight (kg) | 14 | 22 |
| Cranking power at 29C (kW) | > 6 | 4.7 |
| Capacity Ah at C/20 | 45 | 78 |
| Volume (L) | 7 | 11.2 |

discouraged remote relocation of an automotive battery to the vehicle trunk area or passenger area have been the cost of the cabling and shielding needed to support the high current portion of the automotive battery function. By relocating the small TMF™ starter battery in close proximity to the engine compartment; it becomes much more practical to relocate the low-current draw reserve battery in the rear of the vehicle.

Since temperature is the most significant contributor to battery life (with every 9 degree K decrease in temperature resulting roughly in a doubling of battery life), the logistics options enabled by a TMF™ dual battery system could have significant battery-life implications. As a final example, vehicle fuel delivery systems can be designed to operate using the reserve battery, so that they do not see the large voltage variations encountered during vehicle start with a conventional automotive battery.

Perhaps the best match for the performance characteristics of the TMF™ battery is the small engine start application. The lawn and garden tractor start application, as an example, is one that can benefit directly from the high power capability provided by TMF™ without imposing significant reserve capacity demands, thus allowing the tractor to operate with the TMF™ battery as the sole battery.

Although the demonstrated high power performance of the TMF™ battery is extremely promising, there are also challenges that require attention. Although a 5 Ah TMF™ battery can readily provide the high crank currents needed for automotive-start applications, its delivery of those high currents is limited in duration to 10-15s. This time is more than sufficient for a start, but it does not meet the SAE and BCI cold-crank test 30s or DIN 150 s criteria.

Thus, acceptance of the TMF™ dual battery technology in the auto-start application will require acceptance of a change in cold-crank rating convention in addition to the challenges associated with integrating the dual battery system into the vehicle. Work continues to be focused toward demonstrating and improving battery life, high temperature performance, charge sensitivity and stand-loss characteristics. Based on Johnson Controls proprietary battery design and optimization model and test results to date, Johnson Controls is very confident that design optimizations and improvements can be made in this emerging technology that will enable it to fulfill its tremendous potential in a broad array of commercial applications.

## CONCLUSIONS

Although the VRLA battery has lower reserve capacity the charge acceptance of these batteries is higher and so they will get recharged more quickly and efficiently. Since the cost can be brought down by having high production rates as for flooded SLI batteries, the VRLA batteries for automotive use appear to have gained some acceptance and their market share is likely to increase. It is anticipated that these batteries will become more and more popular. The possibility of "dry-out' is excluded because most of the cars manufactured nowadays are fitted with alternator-rectifier system that operates at about 14 V and it should be noted that the top-of-charge voltage of a calcium battery is higher than that of an antimonial battery and so the calcium batteries will be operated in the approximate range of 80-90% state of charge, thus ruling out the possibility of "dry- out".

## REFERENCES


1. B Culpin, K Peters and N R Young, *Power Sources 9, 13th Int Power Sources Symp*, Brighton, (1982) 129-141
2. T M Hardman, *J Power Sources*, **23** (1983) 127-134
3. Takashi Yamada, Yoshio Nakazawa and Naohiro Tsujino *J Power Sources*, **38** (1992) 123-136
4. D Calasanzio, G Cecchinato and M Marchetto, *J Power Sources*, **42** (1993) 247-257
5. K Takahaghi, H Yasuda, H Hasegawa, S Horie and K Kanetsuki, *J Power Sources*, **53** (1995) 137-141
6. K Takahashi, H Yasuda, K Yonezu and H Okamoto, *J Power Sources*, **42** (1993) 221-230
7. K Takahasi, H Yasuda, N Takami, S Horie and Y Suzul, *J Power Sources*, **36** (1991) 451-460
8. `T Isoi and H Furukawa, *J Power Sources*, **59** (1996) 143-146 (also see: M Ohfusa, S Tanaka, T Isoi and H Furukwa, *Yuasa Jiho*, **78** (1997) 17
9. Hongyn Chen and Shuzhan Duan, *J Power Sources*, **62** (1996) 213-217
10. J R Pierson, J P Zagrodnik and R T Johnson, *J Power Sources*, **67** (1997) 7-14
11. Hans Tuphorn, *J Power Sources*, **46** (1993) 361-373
12. Dietrich Berndt, *Maintenance Free Batteries*, First Edition, Research Studies Press, Taunton, Somerset, England (1993) 200
13. J P Douady, C Pascon, A Dugast and G Fossati, *J Power Sources*, **53** (1995) 367-375
14. Tristan Juergans, Micheal A Ruderman and Ralph J Brodd, *36th Power Sources Conference*, June 6-9 (1994) 225-228
15. Bob Nelson, *Proc 12th Annual Battery Conference on Applications and Advances*, California State University, Long Beach, California, (1997) 139-143
16. Ramesh Bhardwaj, Richard Rinehart and Joseph Keating, *Proc 13th Annual Battery Conference on Applications and Advances*, California State University, Long Beach, California, (1998) 303- 309
17. *U S Patent No 5 045 086*, (1991)
18. *U S Patent No 5 047 300*, (1991)
19. *U S Patent No 5 198 313*, (1993)
20. *U S Patent No 5 368 961*, (1994)