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Innovative valve-regulated battery designs rekindle excitement in lead/acid battery technology

John R. Pierson, Jeffrey P. Zagrodnik, Richard T. Johnson

Johnson Controls Battery Group, Inc., Milwaukee, WI, 53201, USA

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Abstract

Recent innovative approaches to the extension of valve-regulated lead/acid (VRLA) technology have led to the development of several unique products that possess performance attributes not previously achieved in lead/acid technologies, namely: (i) starting, lighting, ignition (SLI) VRLA batteries; (ii) StackPack™ foil batteries, and (iii) spiral-wound Thin Metal Film (TMF ™) batteries. The VRLA automotive product has been demonstrated to be capable of improving on the durability of conventional flooded designs in extreme high-temperature climate and extreme drive-cycle operating conditions. In uninterruptible power supply (UPS) applications, the StackPack™ battery, at a 15-min discharge rate has delivered 23.3 Wh kg^{-1} and 1090 Wh l^{-1} as compared with 16.0 Wh kg^{-1} and 595 Wh l^{-1} for traditional designs. TMF™ prototypes have exhibited power capability of an order of magnitude higher than conventional VRLA designs and have been utilized successfully in a vehicle for seven months and over 31 000 km (19 200 miles). © 1997 Published by Elsevier Science S.A.

Keywords: Automotive batteries; Lead/acid batteries; Valve-regulated lead/acid batteries; UPS lead/acid batteries

1. Introduction

The lead/acid battery system has been in existence for over 100 years; it successfully functions in applications that range from vehicle engine cranking to uninterruptible power supply (UPS). Significant evolutionary enhancements in the product design, materials and manufacturing processes have resulted in today's high performance, low cost, dependable product. One of the most important breakthroughs in lead/acid technology occurred with the invention and subsequent development of the gas-recombinant or valve-regulated lead/acid (VRLA) battery. Two versions of this VRLA technology were pursued, one used gelling agents and the other used absorptive glass mat (AGM) separators to immobilize the limited quantity of sulfuric acid electrolyte within the cells. Both of these technologies have been successfully commercialized for various applications throughout the world.

Recent innovative approaches to the extension of VRLA technology, particularly the AGM version, have led to the development of several unique products that possess performance attributes not previously achieved in lead/acid technology. These attributes might facilitate the use of VRLA batteries in new and unique applications.

Three such products that the Johnson Controls is developing, co-developing or evaluating are: (i) starting, lighting and ignition VRLA batteries; (ii) StackPack™ foil batteries, and (iii) spiral-wound Thin Metal Film (TMF™) [1] batteries. The products, which are in various stages of development, all share the AGM design attributes listed in Table 1. While the chemical building blocks from which these three products are made are identical, this is where the similarity ends — their performance characteristics are as varied as the requirements of the applications for which they are designed.

2. Automotive AGM

The desirable features of AGM lead/acid technology — particularly gas recombination, high electrical performance, mounting/location versatility and crashworthiness (no free electrolyte) — would appear to make it a natural for automotive applications. Traditionally, however, the negative attributes of the technology (i.e., intolerance to elevated temperature, charge control sensitivity, expensive materials and processes) have restricted its use to specialized niche applications (Mazda Miata) [2].

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Table 1
AGM lead/acid battery attributes

Absorptive glass-mat separators: no free electrolyte
Non-antimonial grid and top-lead alloys
Controlled cell compression
Gas recombination during operation
Reinforced container
Completely sealed construction with pressure relief-valve
Operable in any orientation
Recycleable materials

The Johnson Controls Engineering team was challenged to design, develop and prove out an AGM product suitable for the automotive aftermarket. To constrain costs, the product was designed for manufacturability on standard assembly equipment and a single model was selected with maximum aftermarket fitment (Battery Council International (BCI) Group 34/78 dual terminal).

Performance ratings of 700 cold-cranking A and 100 min of reserve capacity were specified to meet the application needs of a wide variety of North American vehicles using the BCI Group 34 or 78 geometry. In addition, the design parameters and construction materials were carefully specified to give long life in the extremes of the North American climate. Product features that give the performance and durability required are shown in Fig. 1.

2.1. Grid design

Book-mold cast, radial grid design was selected for the positive electrode to provide the best combination of conductivity and resistance to growth under severe under-hood temperature conditions. Negative grids were also of the book-mold design.

2.2. Grid alloy

Special low-calcium, high-tin alloy with silver and aluminum was specified for the positive grids to provide the most robust corrosion and growth performance under high temperature and high voltage conditions. Development of the valve-regulated automotive product began with low calcium (0.065 wt.%), high tin alloy, but life results of initial taxi fleet studies were short of expectations. Grid growth was the predominant wear-out mode and life was no better than standard flooded product. Given the market goal of superior performance, the lower calcium alloy (0.045 wt.%) with silver was selected. The negative alloy remained the same as that used in conventional flooded automotive batteries, i.e., lead–calcium–aluminum.

2.3. Container

Finite-element analysis was used to design a container with side and end wall strength to maintain compressive force on the cell elements throughout the life of the battery, even though it could be exposed to temperatures of over 100 °C in vehicle service. Container end wall reinforcement is detailed in the isometric drawing, given in Fig. 2.

2.4. Compression

As the first step in creating the uniform compression desired for the VRLA product, both electrodes were pasted to highly uniform thickness and mass using a fixed orifice paster. The cell elements were then assembled with micro-glass separators in a Johnson Controls designed

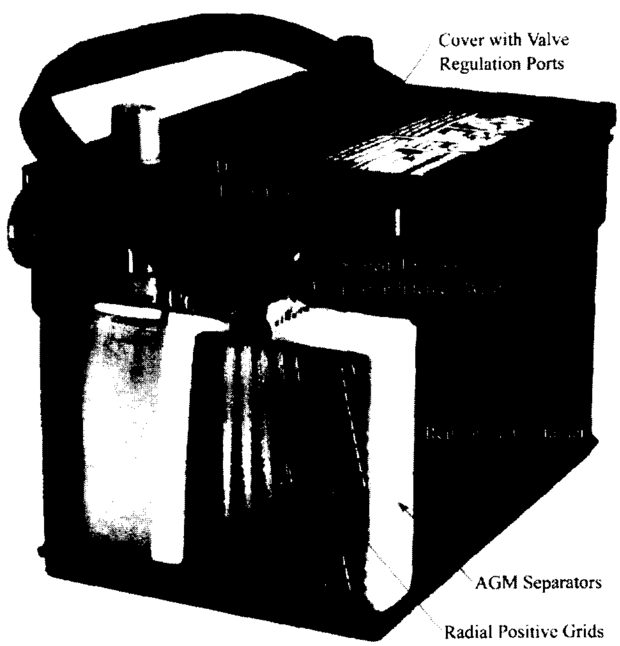

Fig. 1. Automotive VRLA battery features.

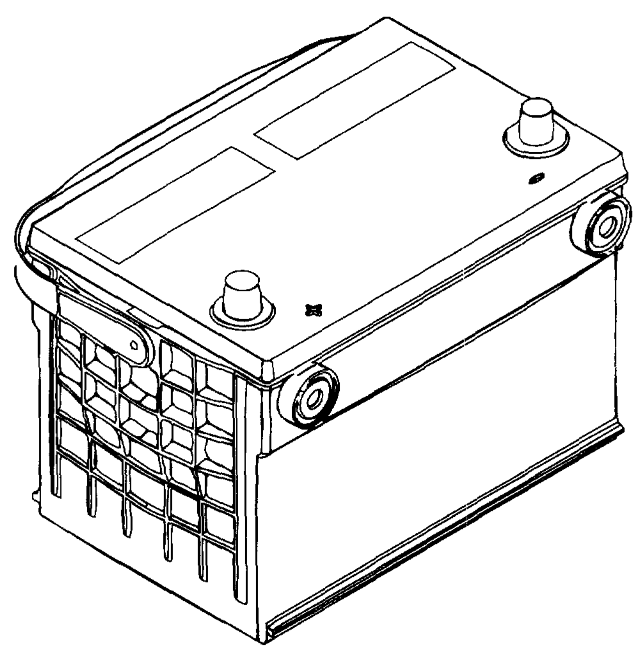

Fig. 2. Automotive VRLA battery case and cover design isometric.

cast-on-strap (COS) and automatically inserted into containers while under compression.

2.5. Dual terminals

The battery design included both top posts and side terminals to increase overall vehicle application fit. Potential vehicle fitment includes over 40% of the North American vehicle fleet.

2.6. Flat top cover with valve-regulation

Individual pressure relief valves were fitted to each cell to eliminate gas phase communication between cells.

2.7. Sealed extrusion / fusion intercell welds

Individual intercell welds of 13 mm diameter were utilized in a design identical to Johnson Controls flooded batteries to also eliminate gas phase communication between cells.

2.8. Performance versus conventional flooded product

Initial electrical performance data confirmed both flooded and VLRA product met their established cold-cranking and reserve capacity ratings. Since valve-regulated product has been considered more susceptible to heat induced wear-out failure than flooded product, most testing focused on high temperature durability testing. Both laboratory life testing and taxi cab fleet testing were used to characterize life under extreme conditions.

Elevated temperature SAE J240 testing was selected for laboratory evaluation because of its acceptance by many world vehicle manufacturers as a valid measure of high-temperature performance and Johnson Controls data that indicated high correlation between it and taxi fleet battery life. The specifics of the test cycle are as follows:

1. place battery in water bath, maintaining temperature at 75 ± 3 °C;
2. discharge for 4 min at 25 A;
3. recharge for 10 min at 25 A to a 14.5 V limit (~ 2.42 V/cell);
4. repeat 430 cycles;
5. rest (up to 68 h) to maintain 1 week per 430 cycles;
6. discharge at cold-cranking rate for 30 s (75 °C), recording voltage, and
7. repeat until voltage at 30 s falls below 7.2 V (1.20 V/cell) for two consecutive weeks.

This procedure is identical to that of *SAE J240 JUN93 Life Test for Automotive Storage Batteries* with two exceptions: (i) the water bath temperature is increased from 40 to 75 °C to simulate better the extreme operating conditions, and (ii) recharge voltage is decreased from 14.8 to 14.5 V because the artificially high 14.8 V limit required to maintain full recharge without significant stratification in flooded batteries is not required in VRLA batteries. Most vehicle regulation strategies utilize 13.0 to 13.8 V for operating conditions resulting in 75 °C battery temperature. Laboratory life cycle test results are given in Table 2. The

Table 2
High temperature (75 °C) SAE J240 cycle test results

Product	Cycles to failure
Conventional flooded hybrid and calcium	2340
Valve-regulated	3230

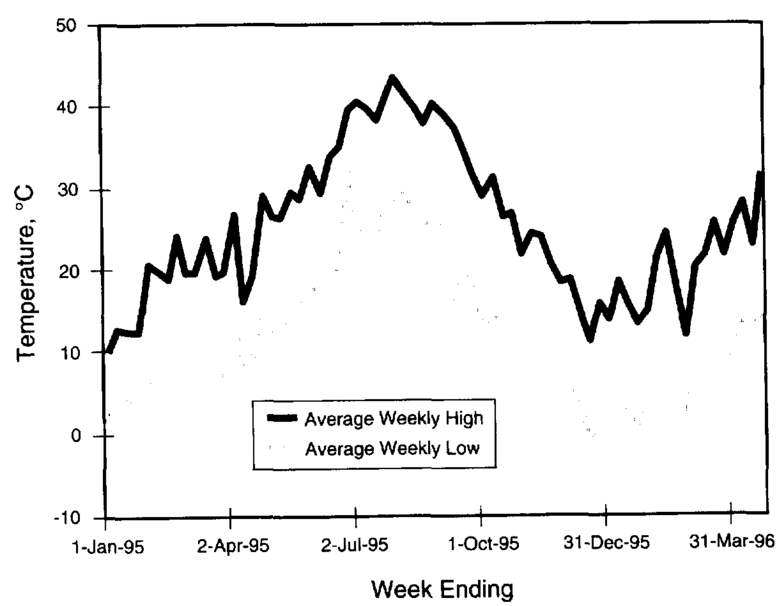

Fig. 3. Las Vegas, NV, USA, climatological data (1995–1996).

Table 3
Taxi fleet life in Las Vegas, NV, USA

Product	Median life (miles)
Conventional flooded hybrid	44000
Valve-regulated	60000

38% improvement in cycles to failure of the VRLA product over flooded product was primarily a result of a change in grid design and the shift to low calcium–tin–silver alloy.

Flooded product wear-out mechanisms were divided between positive-grid corrosion and negative active-material capacity loss. Valve-regulated product wear-out was also predominantly positive grid corrosion, as well as shorting through separators and negative active-material capacity loss.

Taxi cab fleet vehicles in Las Vegas, NV, USA, were selected for field testing because of their near 24 h per day duty cycle and high summer ambient temperature exposure, see Fig. 3. Batteries were installed in unmodified taxi cabs with normal voltage regulation systems. Charge voltage at normal operating conditions was measured to ensure proper operation, but no modifications were made outside of replacement of defective components with new OEM specification replacements.

Vehicles were run normally with standard levels of maintenance. When a battery was removed from a cab for failure to perform, date and vehicle mileage were recorded. Batteries were shipped to Johnson Controls for testing and component examination.

After removing discharged, but serviceable, batteries from the sample, life was determined from cumulative failure percentage plotted against miles in service using the Weibull function. Projected median life results, after return of 15 samples of the 26 installed, are given in Table 3. In spite of the susceptibility of the AGM separators to shorting, the VRLA product gave 36% longer life in hot climate taxi service than flooded batteries of comparable electrical performance.

Failure modes exhibited by conventional product were predominantly positive-grid oxidation/corrosion (and growth for lead–calcium–tin alloys) and active material wear-out. Valve-regulated product failed most frequently by separator shorting and positive-grid oxidation (i.e., corrosion and growth). First failures showed less than 3 mm growth. Greater growth is being seen in higher miles-in-service failures.

Valve-regulated automotive Group 34/78 batteries were subjected to vibration testing according to the procedures outlined in Standards *SAE J930 JUN95, Storage Batteries for Off-Road Work Machines* and *SAE J537 JUN94, Storage Batteries*. Vibration acceleration level was maintained at 5 g_0 (standard gravity acceleration). All batteries completed 200 h of vibration exposure and were capable of continuing when testing was terminated; they surpassed most off-road equipment battery requirements.

In summary, it has been demonstrated that careful attention to critical design parameters of compression, saturation, plate uniformity, cell gas phase isolation, and materials selection has resulted in VRLAs of prismatic design that can be used successfully in automotive applications. Contrary to past experience, this product is capable of improving on the durability of conventional flooded designs in extreme high temperature climate and extreme drive-cycle operating conditions.

3. Stackpack™

StackPack™ is a novel patented [3–8] VRLA battery. The core design has been co-developed by Johnson Controls and Portable Energy Products (PEP). Johnson Controls has focused on multicell designs and applications for the technology and PEP has focused on single-cell designs and applications [9]. Its unique features include a thin, lead foil, current-collector for the plates and a segmented ultrasonically welded container. The design is optimized for moderately high discharge rates, specifically the 5 to 15 min rate of discharge range, and provides dramatically improved run times as compared with conventional VRLA designs at those rates. The high-rate performance capability of the StackPack™ design makes it an ideal candidate for UPS applications, but the general performance characteristics could readily support a wide array of applications.

Fig. 4 shows a StackPack™ 12V500 (12 V, rated at 500 W/battery at the 5 min rate) battery in the background with its individual ABS case segments in the foreground. During assembly, plates and separators are stacked sequentially into each case segment and segments

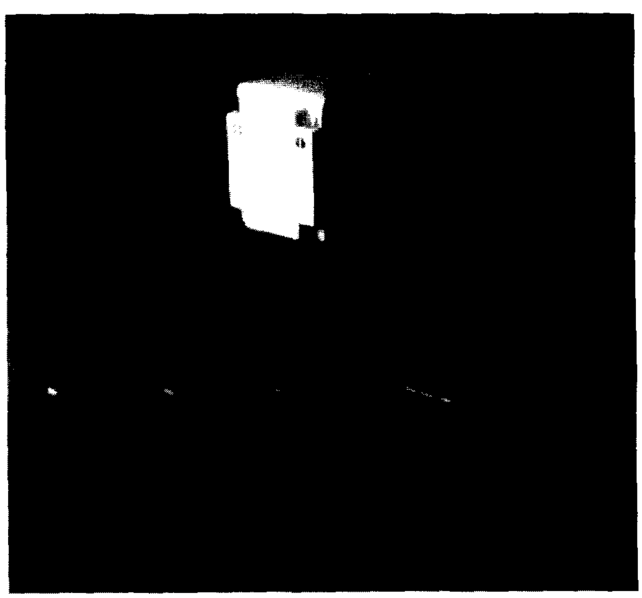

Fig. 4. StackPack™ design.

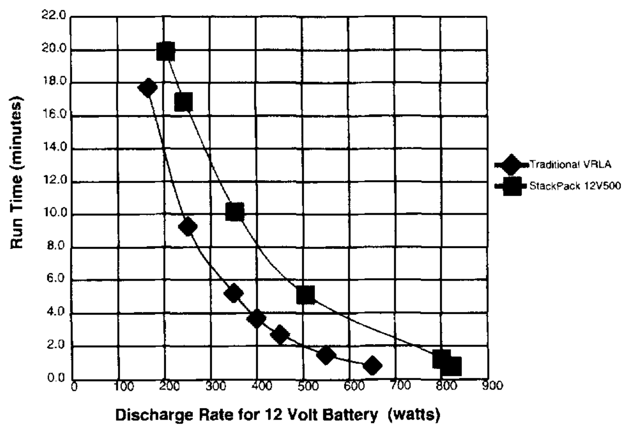

Fig. 5. StackPack™ vs. traditional battery discharge performance at multiple rates (discharge to 10.02 V).

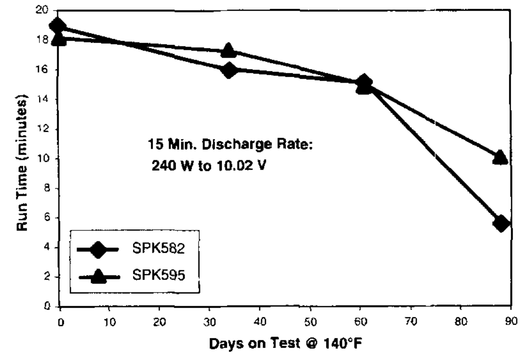

Fig. 7. StackPack™ accelerated float-life characteristics.

are ultrasonically welded to one another to form a cell stack. In this fashion batteries that range anywhere from single cells to 12 V stacks or beyond can be assembled with the same tooling and equipment. The ultrasonic welded assembly provides exceptional control and uniformity in the compression of the individual cells; this is a critical attribute that affects the performance of VRLA batteries.

The run time of a StackPack™ 12V500 battery is compared in Fig. 5 with that of a typical traditional 1270 (12 V, 7 Ah) VRLA battery at varying discharge rates. The external dimensions of the StackPack™ 12V500 battery are 15 cm × 9.4 cm × 6.6 cm (5.9 in × 3.7 in × 2.6 in), exactly the same as those of the traditional design. The StackPack™ battery weighs 2.9 kg (6.4 lb) as compared with 2.3 kg (5.0 lb) for the traditional design. At 270 W discharge, the StackPack™ battery runs for 15 min to a 1.67 V/cell cut-off, 83% longer than the 8.2 min run time of the traditional 1270 design at the same rate. At 270 W, the StackPack™ battery delivers 23.3 Wh kg^{-1} and 1090 Wh l^{-1} as compared with 16.0 Wh kg^{-1} and 595 Wh l^{-1} for the traditional design.

At the 5 min rate of discharge, the differential advantage in the performance of the StackPack™ battery over traditional designs is even greater. At 520 W discharge, the StackPack™ battery runs for 5 min to a 1.67 V/cell cut-off, almost three times as long as the 1.8 min run time of the traditional design at this same rate.

Fig. 6 displays the open-circuit voltage (OCV) stand behaviour of the StackPack™ 12V500 battery at 25, 45 and 60 °C, in comparison with traditional VRLA at 25 °C. As can be seen, the stand loss characteristics are typical of traditional VRLA designs. In other stand tests, the StackPack™ 12V500 delivered 84% of its fully charged capacity at a high (15 min) rate of discharge after 30 days of OCV stand, which also compares favorably with traditional VRLA designs.

Float-life data for an accelerated 60 °C (140 °F) test are given in Fig. 7. Run time is at the 15 min rate of discharge. Every 21 days of test is equivalent to 1 year of real time on float at room temperature. The estimated life of the StackPack™ 12V500 is 3.5 to 4 years, based on an 80% of rated capacity end of life criteria.

Life data for the StackPack™ 12V500 on continuous cycling at the 15 min rate of discharge are presented in Fig. 8. Although cycle life is not a key performance attribute for the float UPS applications of primary interest,

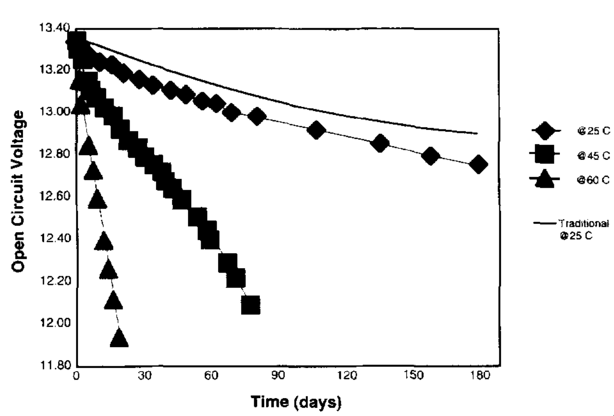

Fig. 6. StackPack™ open-circuit stand loss characteristics.

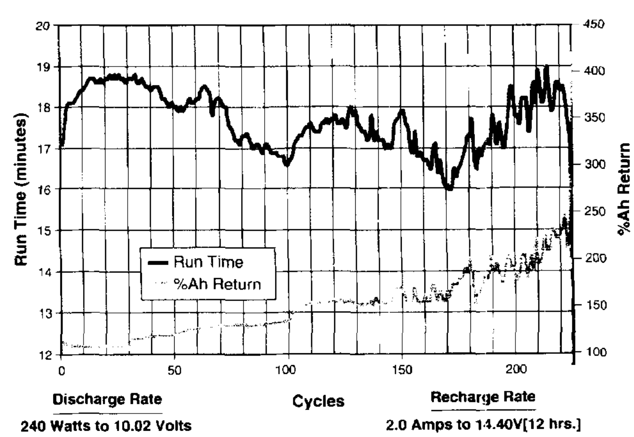

Fig. 8. StackPack™ cycle-life performance (float voltage 2.3 V/cell at 140 °F).

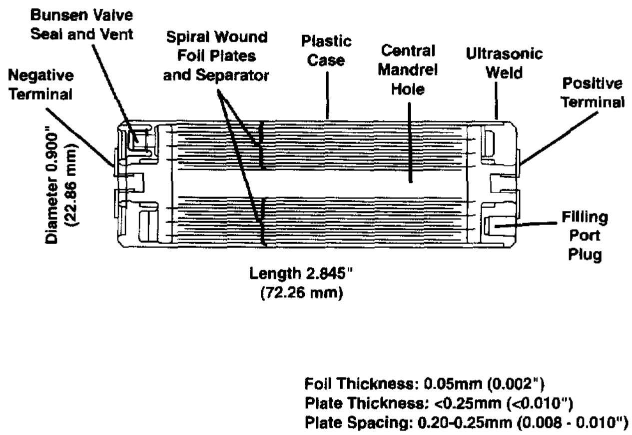

Fig. 9. TMF™ design schematic with features.

it does demonstrate the general design robustness. The excellent high-rate cycle life capability also demonstrates the capability of the design to perform in a wide array of cycling applications.

4. Thin Metal Foil (TMF™)

The Thin Metal Foil (TMF™) battery is another innovative patented [10–13] VRLA design that is optimized for very high power applications. It was initially developed by Bolder Technologies Corporation 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 licensed the TMF™

Fig. 10. TMF™ preprototype installed in vehicle battery tray.

Table 4
TMF™ 1.2 Ah cell performance summary (1.7 V cut-off, room temperature)

Discharge duration(s)	W/cell	W kg^{-1}	W l^{-1}
12	190	2235	6394
15	176	2071	5923
20	160	1882	5384
60	66	776	2221
90	52	612	1750
120	40	471	1346
180	29	341	976
300	21	247	707
360	17	200	572
792	8	94	269
4200	2	24	67

technology for a variety of those applications that include automotive/truck starting and portions of the small-engine start market.

A cross-sectional schematic of the TMF™ cell is provided in Fig. 9. The TMF™ battery utilizes a spiral-wound design and thin-plate construction that parallels that of a capacitor. The design is optimized for high power through the use of extremely thin plates with very high surface area, and a unique termination design that minimizes resistance. The active-material thickness is only 0.2 mm (0.008 in). This results in a very short current path through the active material to the current-collector and a very short diffusion path through the thin active-material layer. The termination design, shown in Fig. 9, allows the entire edge of each plate to contact the cast-on termination puck. The result is a cell resistance of only 2 mΩ for the 1.2 Ah cell and a power capability that is an order of magnitude higher than that of conventional VRLA designs. The design is optimized for very high discharge rates, particularly discharges at the 1 min rate or higher.

Johnson Controls has performed a variety of laboratory and field tests with 1.2 Ah cells to evaluate the TMF™ performance characteristics. Table 4 outlines the power capability of a 1.2 Ah TMF™ cell over a range of constant-power discharge rates.

The most dramatic demonstration of performance to date has been the field test of a 12 V, 2.4 Ah pack of TMF™ cells that has been performing as the starting battery in a passenger vehicle (3.0 l engine) in the Milwaukee, WI area for over seven months. The vehicle has accumulated over 31 000 km (19 200 miles) during the test period. The 1.1 kg (2.5 lb) TMF™ pack directly replaced a conventional Group 65 650 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™ battery was the sole battery in the vehicle. Cranking capability was demonstrated repeatedly at ambient temperatures as low as −29 °C (−21 °F). Fig. 10 shows the TMF™ battery located in the vehicle's battery tray. After six weeks on test, a small VRLA BCI Group U2 battery was added as a reserve battery, with the TMF™ 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™ design is not well suited for low-rate, reserve-type discharges. As in the Johnson Controls field test, the TMF™ 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 5 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™ 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™ 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 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™ start battery in close proximity to the engine compartment, it becomes

Table 5
TMF™-dual battery vs. conventional automotive battery

	TMF™-dual battery	Conventional battery BCI Group 65
TMF™ 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

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 °C 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 10–15 s. This time is more than sufficient for a start, but it does not meet the SAE and BCI cold-crank test 30 s 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.

5. Conclusions

The continuing flow of advances in technology exemplified by the three products described will maintain the viability of the lead/acid battery system for the foreseeable future.

Acknowledgements

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