

Technological progress in sealed lead/acid batteries*

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Abstract

A brief review is given of the history of the research and development of sealed lead/acid batteries during the 30 years since, in 1959, the Yuasa Battery Co introduced a small-sized sealed battery as the power supply for portable television sets. In 1965, Yuasa began the full-scale mass production and sale of a small-sized sealed lead/acid battery under the NOYPER brand. In 1970, the use of a Pb-Ca alloy grid was adopted, and there followed the successful development of a sealed battery with an oxygen-recombination facility. In 1976, Yuasa more or less established the basic technology for the valve-regulated sealed lead/acid battery—the NP battery—which is now the type in general use. Throughout the 1980s, Yuasa, has continued development in order to expand the sphere of application for the production technology of valve-regulated batteries for motorcycles, as well as for stationary duties with large capacities of 100 to 3000 A h. Recently, in order to improve the reliability and boost the output of sealed lead/acid batteries for employment in UPS power sources, Yuasa has been working intently on the design of a valve-regulated lead/acid battery with outstanding characteristics for high-rate discharge and resistance to high temperatures.

Introduction

Over half a century has passed since A. E. Lange's invention, in 1938, of the gas recombination mechanism in which oxygen gas generated during overcharge is consumed by a cadmium negative plate [1]. The technology for practical application of adding the gas-recombination function to the Ni/Cd battery was established in the 1950s, followed by the successful development of the sealed Ni/Cd battery [2, 3].

From the 1960s onwards, basic research and development towards the realization of incorporating gas recombination into the lead/acid battery system was steadily carried out [4]. Today, as a safe and maintenance-free secondary battery, the range of applications of the sealed lead/acid battery has expanded, to penetrate gradually the sealed Ni/Cd battery market. From the 1970s onwards, with the advent of full-scale manufacture and sales, the market for valve-regulated 'sealed' lead/acid batteries has continued to grow rapidly, due to the battery's high-reliability, economy and maintenance-free

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performance At present, the Yuasa Battery Company produces and sells valve-regulated lead/acid batteries ranging in capacity from 0.8 to 3000 A h [5-7] This paper is a simplified outline and review of the research and development of the sealed lead/acid battery that YUASA has been carrying out for the past 30 years

Basic requirements for valve-regulated lead/acid batteries

In terms of both size and capacity, an extremely wide range of valve-regulated lead/acid batteries is presently being manufactured, in three broad categories of capacity (i) small 0.8 to 65 A h, (ii) medium 50 to 100 A h, (iii) large 150 to 3000 A h As far as the basic features of the battery are concerned, clearly, the functions and performance requirements that must be met are largely dependent on the conditions of the given application In general, however, requirements are [9]

- safety
- high output energy density (W h kg^{-1} , W h l^{-1})
- maintenance-free operation
- convenience
- economy

The technological problems that must be solved in order to meet these criteria, and material design, are outlined in Table 1 In order for the valve-regulated design to satisfy the category of safety, not only must it be spill proof, but it must also satisfy the growing demand for improved reliability through the addition of elements such as a facility for estimating remaining life, and non-inflammability

Non-spill, or semi-sealed, small lead/acid batteries for cordless devices

The development and manufacture of lead/acid batteries with a non-spill structure have a long history in specialized applications such as cap lamps employed in mines and batteries used by airplanes With the increasingly widespread use of cordless devices (i.e., portable television, tape recorders, etc.) there has been a gradual demand for an additional function to the non-spill lead/acid battery—a sealed system In 1959, Yuasa developed the PDA battery (a 6 V, 3 A h monoblock construction) as a power source for portable television sets, to be operated on both a.c. and d.c. Some of the basic functions in demand at the time were (i) no liquid leakage, (ii) no acid mist, (iii) cycleability without the need for water addition, (iv) easy handling Further improvements were made to the PDA battery, and these resulted in the development of the semi-sealed system with features that included an ability to be stored for several months, and to be cycled for more than 100 times without requiring the addition of water In 1965, Yuasa embarked upon

TABLE 1

Performance requirements and technological targets for sealed lead/acid batteries

Performance requirements	Technological targets	Materials and design
Large capacity	Improved utilization-efficiency of active material Fixing electrolyte quantity	Conductive additives Reduction of dead space in battery case Flattening of safety valve
High energy density	Compact Lightweight Improved high-rate discharge performance	Improved electrolyte specific gravity Thinner plate Thinner separator Cell construction with higher stacking pressure
Safety factors	Non-leakage Estimation of remaining life Non-inflammability	No free electrolyte Resin sealing Safety valve Explosion preventive filter
Maintenance-free	Reduction of water-loss through battery container walls Achievement of 100% O ₂ -recombination efficiency	Monitoring system Battery container material Laminate construction Microfine glass mat separator
Overcharge resistance	Reduction of electrolyte dry-up speed Improved corrosion resistance of positive grid Improved growth resistance of positive plate	Fixing of electrolyte Positive grid alloy composition Charging system Simulation system
Overdischarge resistance	Improved recharge recovery Improved resistance to short circuit	Electrolyte additives Degree of crystallization of positive and negative active material
Long shelf-life	Reduction of self discharge rate Reduction of auxiliary charge frequency Improved re-charge recovery	Removal of impurities
Long cycle-life Long float-life	No stratification of electrolyte No sulfation No formation of barrier layer in positive grid corrosion film No drying out of electrolyte No thermal runaway Improved corrosion resistance of positive grid Improved resistance to positive grid growth Improved resistance to high-temperature environments	Conductive additives Positive grid alloy composition Microfine glass mat separator Fixing of electrolyte Charging system Estimation of reserve capacity Estimation of expected remaining life Cell construction with higher stacking pressure Battery container material Safety-valve material
Collective assembly	Reduction of unevenness of battery features Simplified connection of batteries Position-free Prevention of temperature rise of battery	Terminal shape Battery voltage Internal impedance of battery Heat-release design Monitoring system Simulation system

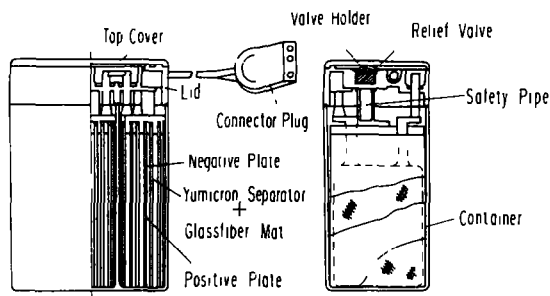


Fig 1 Sectional view of spill-proof, sealed lead/acid battery 'NOYPER' design

marketing this battery under the brand name 'NOYPER' [10] (Fig 1) In order to reduce self-discharge, as well as to reduce water loss during overcharge, a Pb-Sb alloy grid electroplated with pure lead was used To decrease the quantity of free electrolyte, a 1 mm-thick glass mat was inserted between the positive and the negative plates The positives were enclosed in a wrap-around (U-shaped) Yumicron separator As a result, most of the electrolyte was absorbed by the plates, glass mat and separator, thus leaving a minimal amount of free electrolyte Consequently, the protrusion supporting the plate at the base of the casing of the conventional flooded battery became unnecessary

Small-sized sealed lead/acid batteries with gas recombination

With the advent of the 1970s, there was a growing demand for the use of sealed lead/acid batteries as emergency power sources for fire alarms and emergency lighting devices To fulfil this need, research was carried out to realize a practical application of the gas-recombination mechanism in lead/acid batteries so that the floating charge function could be added to sealed systems [5, 11] The following three methods were developed as gas-recombination devices

- (i) recombination of hydrogen and oxygen by a catalyst,
- (ii) absorption by a third electrode,
- (iii) absorption of hydrogen, or oxygen, in the active material of the opposite electrolyte amount

Method (i) was adopted for industrial stationary batteries (see below) In particular, attention was directed towards the development of a catalyst plug Method (iii) was adopted for the small-sized batteries The amount of electrolyte was regulated to the maximum possible, and by the formation of a three-phase interface, between material/liquid/gas, at the negative active material, a sealed lead/acid battery was realized in which the oxygen generated from the positive plate was absorbed by the negative plate [5], Fig 2 In other words, the structural design was such that the height of the negative plate was higher than that of the positive plate in principle, this means that

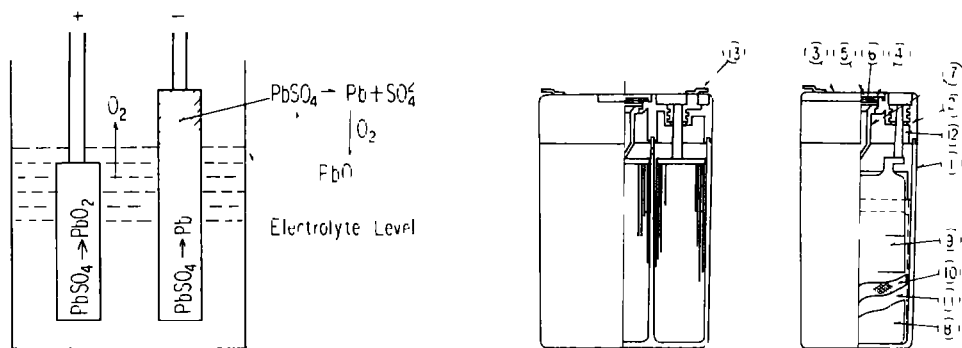


Fig 2 Oxygen-recombination mechanism in improved 'NOYPER' sealed lead/acid battery

Fig 3 Sectional view of improved 'NOYPER' battery with oxygen-recombination mechanism (1) Container, (2) lid, (3) top cover, (4) relief valve, (5) valve holder, (6) fluoro-resin sheet, (7) exhaust sleeve, (8) positive plate, (9) negative plate, (10) electrolyte extensive separator, (11) separator, (12) pole, (13) terminal

the negative plate protruded above the electrolyte level, (Fig 3) The float current and self-discharge rate were reduced appreciably by replacement, in 1970, of the alloy used for the grid and pole strap by Pb-Ca alloy in all versions of the battery. The separator contained glass fibres from 16 to 19 μm in diameter, and with a porosity of 92 to 94%. By regulating the amount of electrolyte in the separator, the free electrolyte was reduced to zero. Meanwhile, in order to prevent totally the expulsion of acid mist from the battery in the event of high-rate recharging, the emission route was re-designed so that the gas would be expelled through a specialized fluoride resin sheet that was microporous and water-repellent.

Small valve-regulated lead/acid batteries for both cycle and float use

Development of glass fibre separator for fixing the electrolyte

As a method for eliminating the liquidity of electrolyte, Yuasa has consistently carried out the development of a sealed lead/acid battery not via the gelled-electrolyte method, but rather through limitation of the quantity of electrolyte and the use of a glass microfibre mat to fix the electrolyte. The performance of the mat separator in fixing the electrolyte is largely influenced by (i) the size of the pores in the separator, (ii) pore shape, (iii) pore distribution. These three factors can be controlled with comparative ease by changing the diameter and the length of the glass fibres. In 1976, Yuasa adopted a non-woven mat (microfine glass fibre mat) that is a blend of fibres of less than 1 μm in diameter (the major component), and several percent of thick fibres of over 10 μm in diameter [12-17].

The velocity at which the electrolyte moves inside the microfibre glass fibre mat separator, that is, the penetrating velocity, is controlled by the capillarity of the separator, and generally is in accordance with the Washburn equation

$$l^2 = \frac{r^2}{4\eta} \left\{ \frac{2\gamma \cos \theta}{r} + \Delta p \right\} t \quad (1)$$

where l is the penetration distance of electrolyte, r is the average pore diameter of the glass mat, γ is the surface tension, θ is the contact angle, η is the electrolyte viscosity (coefficient of viscosity), t is the time, Δp is the difference in pressure between both ends of capillary

With regards to the capillary penetration (rising) velocity through the layer of woven fibre (such as filter paper used in paper chromatography), the Washburn equation, according to Nakagaki and Osagawa [18], can be altered to the following

$$\frac{t}{\tau} = -\frac{h}{h_\infty} - \ln \left(1 - \frac{h}{h_\infty} \right) \quad (2)$$

$$\tau = \frac{8\eta f^2 h_\infty}{(1-\alpha)r^2 \rho g} \quad (3)$$

$$h_\infty = \frac{2\gamma \cos \theta}{r\rho g} \quad (4)$$

where h is the rising distance of electrolyte, η is the electrolyte viscosity, f is the degree of winding of capillary, α is the fraction of electrolyte absorbed by the fibres (in case of glass fibre $\alpha=0$), r is the average pore diameter of glass fibre mat separator, ρ is the electrolyte density, g is the gravity coefficient

Equation (2), when $h/h_\infty \ll 1$, can be reduced to

$$\frac{h^2}{t} = \frac{2h_\infty^2}{\tau} \quad (5)$$

Other than this, it can be altered through Taylor's Theorem to

$$\frac{h^2}{t} = \frac{2h_\infty^2}{\tau} \left\{ 1 - \frac{2}{3} \left(\frac{h}{h_\infty} \right) - \frac{1}{18} \left(\frac{h}{h_\infty} \right)^2 - \dots \right\} \quad (6)$$

and all elements in the series following the square term are extremely small and, therefore, if these are ignored, the final result will be as follows

$$\frac{h^2}{t} = A - Bh \quad (7)$$

so that $h_\infty = 2A/3B$ and $\tau = 8A/9B^2$

To a certain extent, it is possible to judge the ability of the microfibre glass fibre mat separator to fix electrolyte by measuring the velocity at which

the electrolyte is absorbed. Figure 4 shows one example of the results of an experiment in which the speed at which sulfuric acid of 1.30 sp. gr. is absorbed in a vertical direction through the separator was measured when the average pore diameter was altered from 2.5 μm . By applying eqn. (6) and plotting h against h^2/t , a linear graph was obtained over a wide range (Fig. 5).

Improvements in the nature of the corrosion film on Pb-Ca alloy grids

The full-scale use of Pb-Ca alloy in automotive batteries took place in the latter half of the 1970s. Accordingly, there was a significant fall in the price of Pb-Ca alloy. The demand for sealed lead/acid batteries with the added function of gas recombination expanded to include even those areas in which cycle use and float use cannot be differentiated, such as computer terminal devices, medical apparatus, toys, VTRs, UPSs, telecommunications, and engine-driven devices. From around this period, there were growing demands for an improvement in one of the basic requirements of the sealed lead/acid battery, namely, a more complete 'recovery of performance after deep discharge'. As is well known, the recharge recovery performance of the Pb-Ca battery after deep discharge is related to the electrochemical properties of the corrosion film on the positive grid. The corrosion film is essentially a multiphase construction comprised of Pb/PbO/PbO₂ [19, 20], Fig. 6. Recharge recovery after deep discharge is affected greatly by the internal layers of the film, that is, by the formation of the PbO layer. Therefore, basic research was urgently directed towards finding means to control PbO

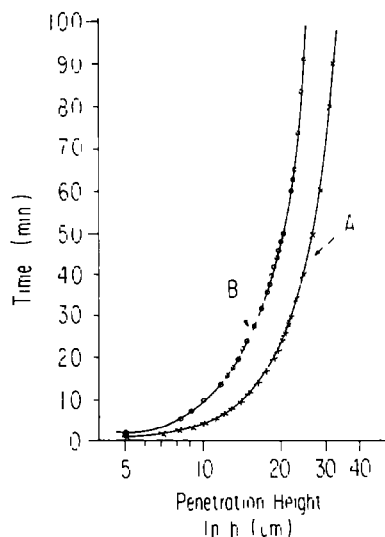


Fig. 4 Relation between time and penetration of 1.30 sp. gr. sulfuric acid through a microfibre mat separator under pressure of 20 kg dm⁻² at 25 °C. Mean pore size (μm) of separator (A) 6.5, (B) 2.5

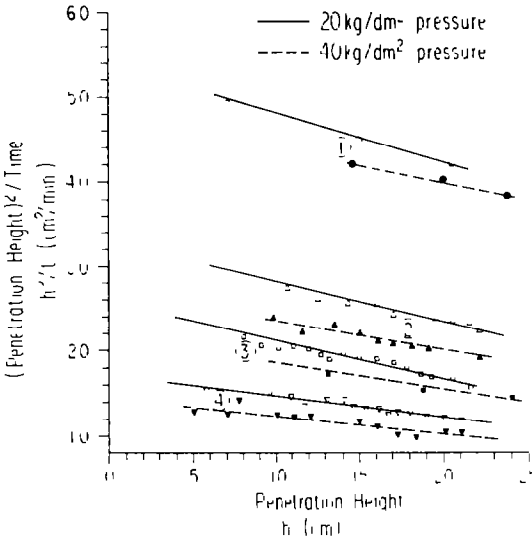


Fig 5 Relation between (penetration height)²/time and penetration height according to Nakagaki and Osagawa [18] when water and sulfuric acids penetrate through a microfine mat separator with a mean pore size of 6.5 μm under pressures of 20 and 40 kg dm⁻² at 25 °C (1) Water, (2) 120 sp gr H₂SO₄, (3) 130 sp gr H₂SO₄, (4) 140 sp gr H₂SO₄

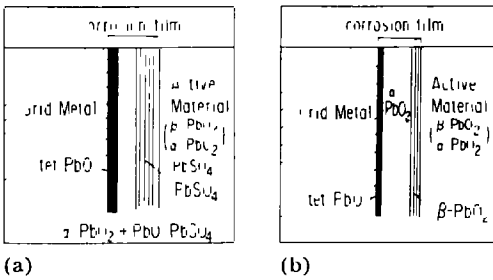


Fig 6 Schematic model of the corrosion film formed on positive Pb-Ca-Sn alloy grids (a) The corrosion film formed after prolonged storage in the fully discharged state (b) The anodic corrosion film formed at high potential

layer formation and to improve the electrochemical properties of the total corrosion film. This research resulted in the discovery that the presence of tin, in some form at the interface between the positive grid and the active material, resulted in a vast improvement on recharge recovery [21-23]. At the same time, it was also understood that the addition of a certain amount of alkaline metal (such as Na⁺ ions) to the electrolyte has the effect of decreasing the speed at which Pb²⁺ ions dissolve in electrolytes with low specific gravity [24-26].

Small valve-regulated lead/acid batteries with complete oxygen-recombination

As a result of the technological development carried out on the positive grid alloy and the microfine glass fibre mat separator, as described above, Yuasa succeeded in establishing the basic technology towards the realization of the valve-regulated lead/acid battery that has continued to be in widespread use since 1976, Fig 7. With this as the turning point, the 'NOYPER' brand, was re-named 'YUASA NP' and introduced into the market in 1976 [27]. Fixing the electrolyte with the use of a microfine glass mat facilitated the formation of the three-phase interface between material/liquid/gas which is evenly distributed across the surface of the active material of the negative plate as a whole (Fig 8). As a result, a reserve area of negative plate of the type traditionally required in the Ni/Cd battery was unnecessary in the sealed lead/acid design, and thus greater economy was achieved. By 1982, the range of NP batteries had grown from 38 to 65 A h, and there are now 22 varieties available [28]. In comparison with the sealed Ni/Cd battery, the NP battery has succeeded in achieving practically the same performance in terms of (i) maintenance-free operation (no water addition required), (ii) no out-gassing, (iii) no liquid leakage, (iv) position-free operation, (v) safe operation in working environments.

Valve-regulated lead/acid batteries for motorcycles

In 1983, under the brand name DINAM (YT series), Yuasa began to sell the valve-regulated lead/acid battery as a maintenance-free unit for motorcycles.

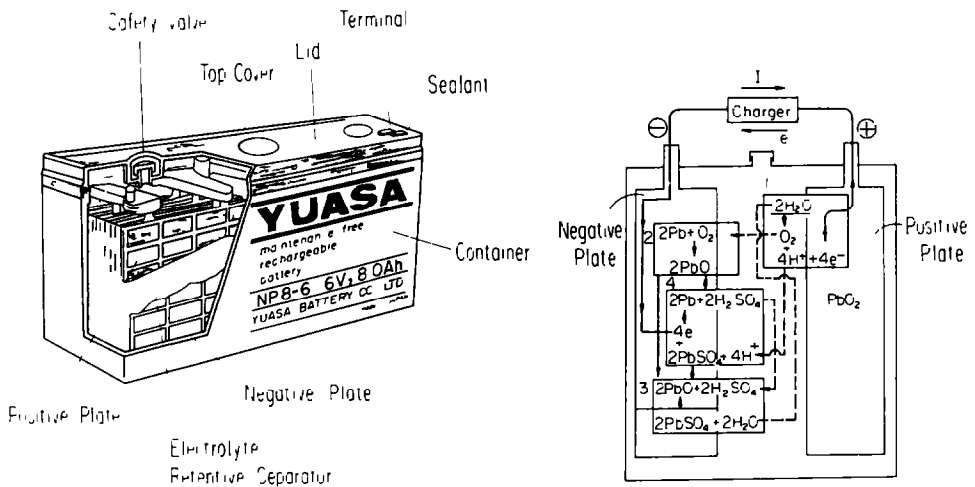


Fig 7 Construction of small-size valve-regulated lead/acid battery, 'Yuasa NP', with excellent oxygen-recombination mechanism

Fig 8 Oxygen-recombination mechanism in 'Yuasa NP' battery

[29, 30], see Table 2 The basic performance features that are demanded for such application are as follows

- high cranking performance
- water topping-up and auxiliary charge unnecessary
- small and lightweight
- position-free operation
- safety
- strong resistance to vibration
- good initial discharge performance of dry-charged units
- low price

Conventional valve-regulated lead/acid batteries are completely charged inside the factory before shipment. Due to the length of the storage periods experienced in distribution and the severity of environmental conditions during transport, a sealed version of dry-charged type used in conventional motorcycle batteries has been adopted. In order to reduce battery cost, heat-sealing of battery container and lid, heat-sealed sealing incorporating a wound resin terminal, a unique exhaust structure, and other features have been introduced, Fig 9. Although the DINAM (YT) series of sealed batteries was primarily developed for use in motorcycles, the performance features can

TABLE 2

Development history of the DINAM (YT) valve-regulated lead/acid battery for motorcycles

Date	Battery	Voltage (V)	C/10 Capacity (A h)	Customer	Note
Nov '83	YT4L-12	12	3	Honda	
	YT5L-12	12	4	Honda	
	YT12-12	12	10	Honda	
Feb '85	YT4L-12B	12	3	Honda	Different terminal shape of YT4L-12
	YT5L-12B	12	4	Honda	Different terminal shape of YT5L-12
Apr 85	YTH12-12B	12	10	Honda	Improvement of cranking ability and different terminal shape of YT12-12
June 85	YTH14-12B	12	12	Honda	New type
July 85	YTH9-12B	12	8	Honda	New type
June '86	YTH5L-12B	12	4	Suzuki	Improvement of cranking ability of YT5L-12B
Aug '86	YTH7A-12B	12	6	Honda	New type
Sept '86	YTX9-12B	12	8	Honda	Improvement of cranking ability of YTH9-12B
Nov '87	YT4L-BS	12	3	Honda	Improvement of filling method
	YTX7L-BS	12	6	Honda	New type

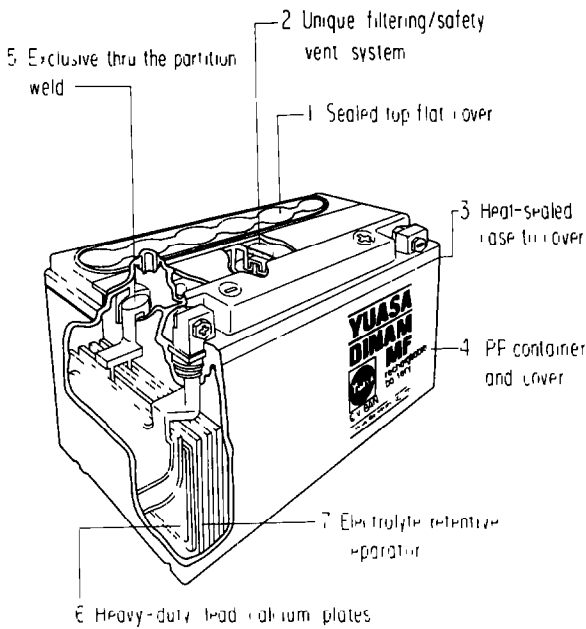


Fig 9 Construction of valve-regulated lead/acid battery for motorcycles, Yuasa DINAM'

be readily applied to, for example, snowmobiles, water scooters, wheelchairs, and motor-driven tools

Valve-regulated lead/acid batteries for industrial stationary use

In order to add the gas-recombination function to stationary lead/acid batteries, Yuasa developed the catalyst system and first began marketing this product in 1969 [31]. Since then, four different types of catalytic plugs have been designed for industrial batteries ranging from 15 to 8010 A h [6, 8]. The catalyst plugs are inserted into the electrolyte filling hole of the flooded stationary batteries. Under normal conditions, it is possible to extend the period required for water topping-up to at least three years. Nevertheless, as a decrease in gas-recombination efficiency of the catalyst is unavoidable during service, replacement is normally effected every 3 to 5 years. Although the maintenance-free level of stationary lead/acid batteries with catalyst plug is low, results have shown that such systems can be used over long periods with a high degree of reliability. Therefore, to obtain a completely sealed type of stationary battery, it was necessary to develop a valve-regulated system with an even higher degree of reliability.

The following basic requirements must be met when adding the oxygen-recombination function to industrial lead/acid batteries in a manner similar to that successfully achieved with the above-mentioned small-sized valve-

regulated units with less than 65 A h, in which the strategy involved allowing the oxygen gas to be absorbed by the negative plate

- improvement in high-rate discharge (i.e., 1-h rate)
- float service life longer than 10 years
- position-free operation
- reduction of battery standing space
- no out-gassing to a level enabling installation in an office

In order to expand the application of valve-regulated lead/acid batteries to include industrial use, technological development was carried out by Yuasa throughout the 1980s, with the aim of upgrading the absolute capacity. This work resulted in the introduction of the 30 to 100 A h class in 1983, the 150 to 500 A h class in 1986, and the 1500 to 3000 A h class in 1988 [32–35] (Fig 10). The energy densities ($W h l^{-1}$) of sealed and flooded batteries are compared in Fig 11. The vast superiority of the sealed battery is clearly evident. The valve-regulated design also has the advantage of no out-gassing, and when applied to telecommunication service, for instance,

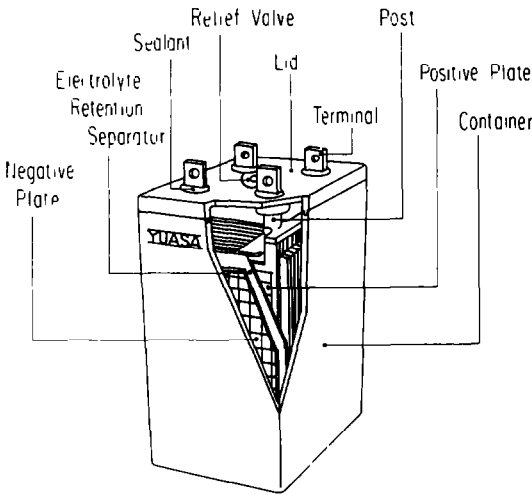


Fig 10 Construction of stationary valve-regulated lead/acid battery, 'UXL'

Rate	Battery Type	Volumetric Energy Density (Wh/l)						
		10	20	30	40	50	60	70
10 h	Sealed						136 %	
	Flooded				100 %			
1 h	Sealed				153 %			
	Flooded				100 %			

Fig 11 Comparison of specific volumetric energy density ($W h l^{-1}$) for stationary sealed 'UXL and conventional flooded batteries

the installation of a special battery room (necessary in the case of flooded batteries) is not required, sealed batteries not only can be installed in the same location (or floor) as the control apparatus or devices, but also can be positioned inside offices where people are working. Particular emphasis has been placed on battery safety. For example, the exhaust section has a ceramic filter to prevent explosions, and the cross-sectional area of the terminal has been enlarged to a maximum value, Fig 12. Technological development is presently being carried out to estimate the reserve capacity and expected remaining life of the battery by introducing a monitoring and simulation system.

Future prospects for valve-regulated lead/acid batteries

Development of units with improved high-rate discharge performance

In recent years, with the increasingly widespread use of micro-computer controlled devices and computer mechanisms, the demand is growing rapidly for a low-priced valve-regulated lead/acid battery for UPS power sources. In 1986, Yuasa commenced marketing such a battery under the brand name 'NPH'. The basic performance requirements for such a battery are

- high output density ($W h l^{-1}$, $W h kg^{-1}$)
- improved high-rate discharge performance
- long float-life
- no out-gassing

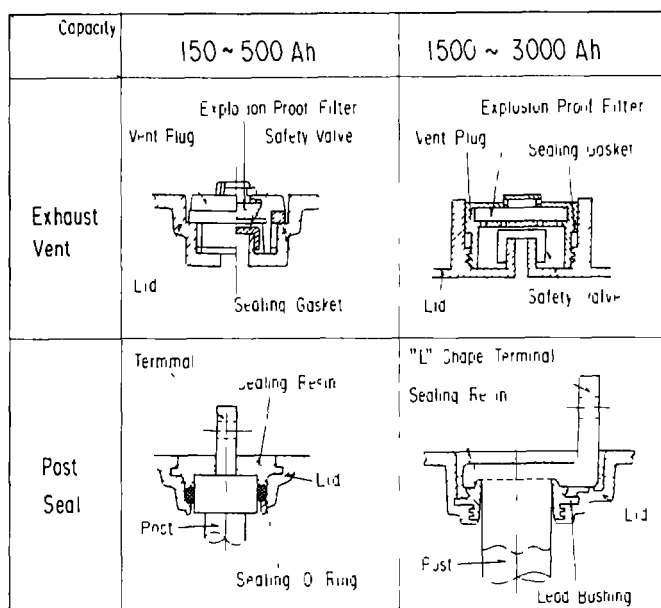


Fig 12 Construction of the exhaust vent and post seal in stationary sealed 'UXL' battery

- no acid leakage
- position-free operation
- easy connection of batteries
- strong resistance to high-temperature operation (no thermal runaway)
- low price

One of the feature of the NPH series is a high-rate discharge performance that enables a 10-min back-up during 3 C discharge [7, 16], Fig 13

A summary of Yuasa's products is given in Table 3 At present, the NPH series of batteries is being designed with an expected float-life ranging from 3 to 5 years. However, in order to improve further the maintenance-free performance and high reliability of UPS batteries, there is the necessity to develop an NPH battery with a float-life longer than 5 years At the same time, demands dictate that the present high-rate discharge performance (1 to 10 min rate) be increased by a factor of 1.5 to 2

Development of valve-regulated lead/acid batteries for use in high-temperature environments

With the present rapid growth in the use of sealed lead/acid batteries for UPS use, the tendency exists for a gradual rise in the temperature of the environment in which the batteries are used. In the majority of UPS services, to achieve either 48 or 96 V, the batteries are connected in series and placed in a box There is a growing tendency for more compact UPS and parts density, which includes the battery box Therefore, the importance of a heat-release design of battery, including the storage box, has increased As shown in Figs 14 and 15, however, the float current of valve-regulated batteries typically exhibits a sudden rise when the temperature exceeds

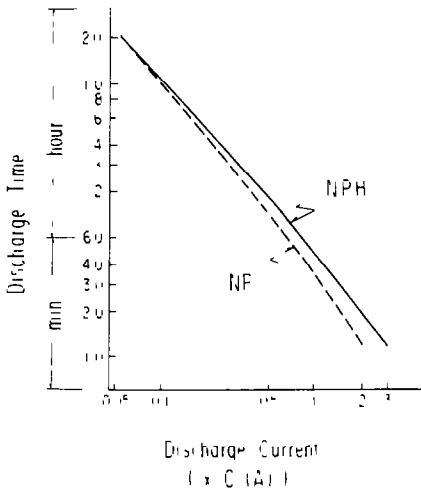


Fig 13 Peukert plot between discharge time and discharge current of Yuasa NPH' battery for UPS service

TABLE 3
Valve-regulated lead/acid batteries manufactured by Yuasa

Battery series					
	NP	NPH	UXL	DINAM (YT)	
Application	Solar powered system Telecommunication Medical equipment Portable TV Portable recorder Alarm system Fire and security System Power tools UPS etc	UPS	Stationary		Motorcycles Mopeds Snowmobiles Water scooter Toys and models Wheelchair Lawn mowers Garden tractors Electric tools etc
Voltage/Capacity	6-12 V/0.8-65 A h	6 V/1.3-3.2 A h 12 V/3.2-16 A h	12 V/30-50 A h 6 V/60-100 A h 2 V/150-3000 A h		12 V/3-12 A h
Expected life (20 °C)	Standby service 3-5 years Cycle service 100% DOD 180 cycles 50% DOD 400 cycles 30% DOD 200 cycles	Standby service 3-5 years	Standby service 10-15 years		

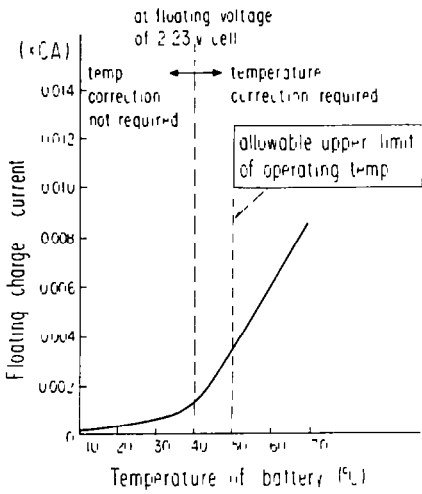


Fig 14 Relation between temperature and floating current of the stationary sealed UXL' battery

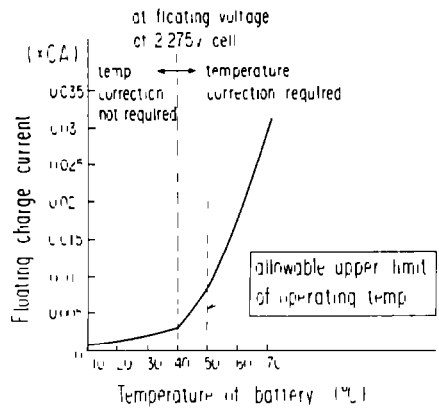


Fig 15 Relation between temperature and floating current of the small-size sealed Yuasa NP' battery

40 °C [37] Thus, present conditions dictate that the maximum temperature allowable when using such batteries is approximately 50 °C. Meanwhile, research and development have continued since 1983 towards the realization of a valve-regulated battery that can be used as an automotive battery. Due to the limited amount of electrolyte in the sealed design, the heat capacity is smaller than that of the flooded counterpart and, therefore, when placed in a high-temperature environment, the sealed battery tends to rise in temperature more easily and must increase resistance to drying out of the electrolyte. To achieve further significant growth in the range of applications of valve-regulated lead/acid batteries, it will be necessary to develop low-price materials that will enable the allowable temperature of battery operation to be raised to 70 to 80 °C.

Conclusions

This paper outlines the past 30 years of technological research of the sealed lead/acid battery system during which it has become a safe, highly reliable and maintenance-free product. It is clear that the present range of applications will continue to expand and develop during the 1990s. In particular, research is being directed towards securing additional features such as (i) advanced high-rate discharge performance, (ii) improved practical use in high-temperature environments, (iii) longer cycle- and float-life.

