

The development of tubular-plate batteries has gained popularity as this technology is claimed to possess several advantages over flat-plate batteries. These are:

(i) greater mechanical stability (i.e., reduced shedding) – the positive active-material is contained securely in a porous, woven tube;

(ii) improved mass utilization – more porous active material can be used (at high currents, however, the performance is lowered due to the greater thickness of the tubular plates);

(iii) more uniform current distribution throughout the active material – the current collector (i.e., the spine) is located centrally;

(iv) reduced grid corrosion – the spine is protected by the thick layer of active material, and

(v) superior active-material/grid weight ratio (note, however, the contact area between the material and the spine is small, so that local heating may occur during prolonged high-current discharge; this, in turn, may crack part of the corrosion layer and thus expose the spine to further corrosion and also increase the electrical resistance).

The silicon dioxide, or 'fumed silica', used in the construction of the gelled-electrolyte batteries has a very small average particle size (approximately 10 nm) and, consequently, has a high surface area (up to 400 m² g⁻¹). On mixing with sulfuric acid, the fumed silica (typically 3 to 5 wt.%) forms a viscous solution that develops into a gel on standing. The 'thickening' action can be reversed by subjecting the material to a significant impact, although the gel will reform if the solution is not disturbed. It is thought that weak hydrogen bonding is responsible for this phenomenon. It is referred to as thixotropy and forms the basis for the production of the gelled-electrolyte battery.

In AGM batteries, the sulfuric acid is absorbed into a glass-microfibre separator that consists of a blend of glass fibres of varying lengths and diameters. Good movement of the acid along these glass strands of the AGM (known as 'wicking') is necessary for satisfactory operation of the batteries. Initially, it was thought that thin fibres with a high surface area (1.6 to 2.0 m² g⁻¹) were required to achieve this action but, recently, it has been established that low surface-area strands (1.1 to 1.3 m² g⁻¹) can provide acceptable performance at a much reduced cost. The AGM is usually saturated with acid to between 90 and 95% of its maximum, while the remaining volume allows the passage of gas so that recombination can occur (see below). The AGM separators must be in intimate contact with the plates, to allow fast transfer of ions during charge and discharge of the batteries. To achieve the appropriate 'stack pressure', a close, tight fit is required between the cell group and the battery container.

The following sections describe in detail both the advantages and disadvantages of using VRBs as the

energy storage medium in power-supplies. A summary is also given in Table 1.

2. Advantages of valve-regulated batteries

The major advantage of VRB technology is that it does not require any water maintenance. This is due to the fact that the oxygen produced at the positive plates during charging is reduced to water at the negative plates [2,3]. This 'recombination' reaction is promoted by incorporating the following design features into the batteries:

(i) the positive-to-negative stoichiometric ratio of active material is kept close to unity, so that gassing occurs at the positive plate before the negative plate; liberated oxygen diffuses to the negative, where it reacts with metallic lead and sulfuric acid to form lead sulfate and water;

(ii) antimony is not generally employed in the grid alloys;

(iii) a non-flooded electrolyte system is used, this enhances diffusion of oxygen from the positive to the negative plates;

(iv) the battery is sealed and operates under pressure in order to assist the rate of oxygen recombination, and

(v) a venting device (i.e., a valve) is fitted that allows the release of excess gas.

As VRBs are sealed, acid spillage will not occur unless the battery case is ruptured. Even then, the amount of acid that can escape from the battery is minimal because of the immobilized nature of the electrolyte. The low risk of acid leakage results in simple transport arrangements, i.e., VRBs can often be conveyed as non-hazardous cargo by both air and sea. By contrast, 'wet' flooded-electrolyte units are always classified as hazardous freight. This latter category requires special packaging and results in additional shipping costs.

VRBs emit negligible quantities of sulfuric acid and hydrogen gas under normal operating conditions. Hence, there are no special ventilation requirements for VRB enclosures. In addition, the corrosion of metal surfaces within the battery room, including battery posts and connectors, will be insignificant. Moreover, the risk of a hydrogen gas explosion is much reduced. All these factors result in a much simpler battery room that is less expensive to establish and maintain, and also allow batteries to be placed in close proximity to sensitive electronic equipment and appliances. VRBs are especially attractive for systems located in cities where the cost of real estate is high. These units can be operated on their sides in racks, and this reduces the floor space required. Such an arrangement also facilitates routine checks of the state-of-health of batteries.

Table 1
Advantages/disadvantages of valve-regulated batteries with respect to flooded-electrolyte batteries

Advantages	Disadvantages
No water addition	Careful charging required
No acid spillage	Thermal management is more critical, especially for AGM batteries
Negligible acid fumes	Significant variation in top-of-charge voltages
Easy transportation	Increase in overcharge required at elevated temperatures
No special ventilation requirements	Deep-cycle life often inferior under optimum operating conditions
Can be operated horizontally	Cannot measure specific gravity
Smaller footprint (batteries can be multistacked)	Not available in dry-charge state
Negligible acid stratification (gel-type only)	Shelf life of two years maximum
Less overcharge required at room temperature	
Good high-rate, discharge capacity (AGM type only)	

2.1. Gelled-electrolyte batteries

Minimal stratification of the electrolyte occurs during the operation of gelled-electrolyte batteries [2]. This is important because the phenomenon has been responsible for the premature failure of many flooded-electrolyte battery banks. The mild level of stratification experienced by gelled-electrolyte batteries means that at normal temperatures [4–6], less overcharge is required to fully recharge and equalize the battery units (i.e., generally 103 to 105%). Moreover, after extensive laboratory and field evaluations under RAPS service, this design of battery has been shown to be suitable for such severe duty [6,9–13].

2.2. Absorptive glass-microfibre batteries

AGM units undergo significant electrolyte stratification [6–8], albeit less than that of their flooded-electrolyte counterparts. Operation of AGM batteries has been found [6,9–13] to be problematical under deep-cycle conditions where a regular, well-regimented charging regime is not guaranteed, e.g., RAPS systems. In some cases, the poor performance has been related to stratification of the electrolyte within these batteries. AGM batteries do, however, have a very low internal resistance. As a consequence, they have excellent high-rate discharge capacities. Therefore, it is considered that AGM batteries are more suitable for UPS, standby and possibly SLI applications, where charging periods and conditions are both predictable and well-regulated.

3. Disadvantages of valve-regulated batteries

The major complication with the use of VRB technology is that very accurate control must be placed on the charging regime. If cell voltages are allowed to rise above a certain level (usually 2.35 to 2.40 V/cell, depending upon the manufacturer), the batteries are often unable to recombine all of the oxygen that is produced.

At elevated potentials, hydrogen (which is recombined to only a small extent) is formed at the negative plates. The subsequent pressure build-up can result in the loss of water from the battery.

In most instances, gelled-electrolyte batteries can be successfully charged using a constant-current/constant-voltage regime. As mentioned above, AGM batteries that are subjected to regular deep-discharge conditions require special charging regimes to avoid the formation of electrolyte stratification. An effective charging strategy is as follows: (i) constant current until recombination has commenced, i.e., about 2.45 to about 2.5 V/cell, and (ii) a lower value of constant current until a preset voltage change (dV/dt) has been reached. Obviously, in some applications (e.g., RAPS duty) sufficient power cannot always be guaranteed for such a charging procedure. As precise charging is required for a VRB bank to deliver its optimum performance/lifetime, microprocessor control with well-established algorithms is essential.

The recombination reaction within VRBs during charging, involves the reaction of oxygen with the lead of the negative plate. This interaction produces heat that cannot escape readily from a sealed design of battery. Hence, the internal temperatures of VRBs can exceed those of equivalent flooded-electrolyte units. This results in the former batteries, especially the AGM design, being more susceptible to thermal runaway [14,15]. This phenomenon can be defined as 'an increase in battery temperature due to uncontrolled, internal exothermic reactions' and can result in the battery catching fire. Gelled-electrolyte batteries are less susceptible than AGM units to thermal runaway because the former have a lower internal heat generation (due to lower float currents) and a higher heat transfer. Therefore, consideration must be given towards: (i) positioning of the batteries in the battery bank, and (ii) passive cooling and/or recirculation of air in the battery room.

With gelled-electrolyte batteries, oxygen transfer occurs via fissures in the substrate that form during the

early stages of battery life through partial drying out (water loss) and concomitant shrinkage of the gel (it is also thought that some transport of oxygen occurs via bonding and movement along the silica chains of the gel [16]). As a result, cells in series at the beginning of service can exhibit: (i) different recombination rates; (ii) varying top-of-charge voltages (TOCVs) (by up to 250 mV [2]), and (iii) significant water consumptions. After the initial 'running-in' period, these features usually decrease to much lower levels, although the variation in the TOCVs is always considerably higher than that of flooded-electrolyte batteries.

With AGM technology, the porous matrix is not fully saturated with electrolyte, hence the remaining free volume allows the passage of oxygen to the negative plates. Drying out of the electrolyte, with the subsequent stabilization of TOCVs also occurs in these batteries, but to a lesser extent than that for gelled-electrolyte units. In general, after the initial 'conditioning' water loss, the deviation in TOCVs in strings of both gelled-electrolyte and AGM cells is similar.

Under stand-by conditions (constant voltage of 2.2 to 2.3 V), some controversy exists as to the relationship between the float voltages and capacities of individual VRB cells. Some researchers have demonstrated that there is little correlation between the voltage of a VRB on float and the delivered capacity [17,18]. Others [19] have found that the float voltages of individual cells within a 180 cell series string varied by only 30 mV, and that during heavy cycling, capacities remained in balance throughout the string. Charging in the latter investigation, however, was conducted for 60 to 70 h at a constant voltage of 2.37 V/cell. Hence, it appears that charging at higher potentials (i.e., >2.35 V/cell) for extended periods can be beneficial in reducing significantly the deviation in TOCVs.

In long strings of either VRBs or flooded-electrolyte batteries, there is a tendency for the capacity of individual cells to become unequal, i.e., some cells slowly decrease in capacity relative to others. In extreme situations, some cells can be driven into reversal during discharge. This behaviour can be exacerbated by: (i) large differences in initial cell state-of-charge; (ii) variable product quality, e.g., uneven pasting of plates; (iii) very long strings; (iv) deep and continuous cycling, and (v) inadequate charging. VRBs are more susceptible to this phenomenon than their flooded-electrolyte counterparts because of variations in recombination efficiencies (see above). The use of appropriate charging procedures, however, minimizes the occurrence of major imbalances in cell capacities. It is considered [13] that microprocessor control, combined with carefully developed charging algorithms, can reduce this risk to a negligible level.

It has been shown [5,6] that VRBs (both gelled-electrolyte and AGM designs) require additional charge

time and overcharge at elevated temperatures (e.g., about 45 °C). This behaviour has been related to a lowering of the charge acceptance of the battery [5,6]. If extra charging is not provided, the capacity of the battery slowly falls and causes a further reduction in charge acceptance. Hence, unless the battery is charged during periods of lower temperature, e.g., night-time, more energy will be required to charge the battery. For RAPS systems powered only by photovoltaic arrays, the size of these latter components may have to be increased to compensate for the decrease in charging efficiency.

As mentioned above, laboratory and field evaluations have shown that gelled-electrolyte batteries can provide acceptable service lives under RAPS service [6,9–13]. It has also been demonstrated [6,13] that the best flooded-electrolyte battery, if properly operated and maintained, will usually outlast similar sized gelled-electrolyte units. Also, AGM units have been shown to perform poorly under such duty, and, at their current state of development, are not recommended for deep-cycle service where the charging regime is not strictly controlled.

A further operational disadvantage of VRBs is that the specific gravity of the electrolyte cannot be measured unless the battery is disassembled. Hence, cell voltage and string current are the only parameters that can be used to evaluate the condition of batteries. In addition, VRBs are not available in a dry-charged state. As a consequence of this, VRBs have a shelf life of only two years. (Note, dry-charged, flooded-electrolyte batteries if sealed and airtight, can have a shelf life of over five years.)

4. Summary

The most important benefit of VRBs is that they do not require water maintenance. They do, however, require very careful charging, to the extent that microprocessor control is strongly recommended for adequate service life to be achieved. Gelled-electrolyte batteries offer acceptable deep-cycle performance. At present, AGM batteries are not suitable for deep-discharge service where regular, well-controlled charging is not guaranteed, but are favoured for UPS and stand-by applications as they provide an excellent high-rate, discharge performance. Finally, it is important to realize that the VRB technology is not totally maintenance free. Maintenance of the terminals and connectors is still required, but to a much lesser extent than for flooded-electrolyte batteries.

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References

- [1] M. Shiomi, K. Takahashi and M. Tsubota, *J Power Sources*, 42 (1993) 173.
- [2] H. Tuphorn, *Rev Gen Electr*, 3 (1990) 45
- [3] H. Dietz, M. Radwan, J. Garche, H. Doring and K. Wiesener, *J Appl. Electrochem.*, 21 (1991) 221.
- [4] B.L. McKinney, B.K. Mahata and K.R. Bullock, in K.R. Bullock and D. Pavlov (eds.), *Advances in Lead-Acid Batteries*, Proc. Vol. 84-14, The Electrochemical Society, Pennington, NJ, USA, 1984, p. 426.
- [5] W.H. DeLuca, A.F. Tummillo, C.E. Webster, R.L. Hogrefe and F. Miller, *Proc 25th Intersociety Energy Conversion Engineering Conf, Reno, NV, USA, Aug. 1990*, Vol. 3, p. 320.
- [6] W.G.A. Baldsing, R.D. Bramley, R.H. Newnham and C. Power, Lead/acid batteries for remote-area energy storage, *ERDC Project No. 1525, Final Rep., Feb 1993*, CSIRO Division Mineral Products, Melbourne, Australia, *Communication MPC/M-379*
- [7] K. Higashimoto, A. Miura, T. Hayakawa and A. Komaki, *Prog Batteries Solar Cells*, 8 (1989) 268.
- [8] Y. Nakayama, T. Nagayasu, K. Kishimoto and Y. Kasai, *Yuasa Jho*, 71 (1991) 46.
- [9] W.G.A. Baldsing, K.K. Constanti, J.A. Hamilton, P.B. Harmer, R.J. Hill, D.A.J. Rand and R.B. Zmood, Lead/acid batteries for remote-area energy storage, *NERDDC Project No. 904, Final Rep, Apr 1988*, CSIRO Division Mineral Chemistry, Melbourne, Australia, *Communication MCC-837*.
- [10] W.G.A. Baldsing, K.K. Constanti, J.A. Hamilton, A.F. Hollenkamp, C. Power, R.H. Newnham, D.A.J. Rand and D.G. Vella, Lead/acid batteries for remote-area energy storage, *NERDDC Project No. 1133, Final Rep., Jan. 1991*, CSIRO Division Mineral Products, Melbourne Australia, *Communication MPC/M-222*.
- [11] W.G.A. Baldsing, J.A. Hamilton, A.F. Hollenkamp, R.H. Newnham and D.A.J. Rand, *J. Power Sources*, 35 (1991) 385.
- [12] H.P. Hones, A. Jossen, A. Bosch, H. Karl, G. Lehner, G. Saupe and A. Zahir, *Proc 11th European Photovoltaic Solar Energy Conf. and Exhibition, Montreux, Switzerland, Oct. 1992*
- [13] R.H. Newnham, W.G.A. Baldsing and R.D. Bramley, Assessment of battery technologies and system configurations for RAPS duty, *ILZRO Proj. LD-433, Sept 1993*, CSIRO Division Mineral Products, Melbourne, Australia, *Communication MPC/M-415*.
- [14] S.G. Gerner, G.H. Brilmyer and D.H. Bornemann, *12th Int. Telecommunication Energy Conf., INTELEC 1990, Orlando, FL, USA, Oct 1990* p. 1.
- [15] B. Culpin and D.A.J. Rand, *J Power Sources*, 36 (1991) 415.
- [16] W.B. Brecht and N.F. O'Leary, *10th Int. Telecommunication Energy Conf., INTELEC 1988, San Diego, CA, USA, 1988*, p. 35.
- [17] A.I. Harrison and R.P. Bullough, *Proc. 12th Int Telecommunication Energy Conf, INTELEC 1990, Orlando, FL, USA, Oct. 1990*, p 213.
- [18] D. Kuhn, *New Exchange Power System IEEE, ALDA, GNB Seminar on Lead/Acid Batteries, Sydney, Australia, Nov. 1992*
- [19] S.L. Desphande, *Proc. 3rd Int. Lead-Acid Battery Seminar, Orlando, FL, USA, International Lead Zinc Research Organization, Research Triangle Park, NC, USA, 1989*, p 235.