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Performance of lead/acid batteries in remote-area power-supply applications*

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Abstract

A detailed evaluation is made of the performance of a wide range of lead/acid battery technologies operating under both simulated and field conditions encountered in remote-area power-supply (RAPS) duty Laboratory studies indicate that the most promising designs of battery are (i) flat-plate, flooded-electrolyte, with thick plates and low-antimony positive grids, (ii) tubular-plate, flooded-electrolyte, with granular oxide (iii) flat-/tubular-plate, gelled-electrolyte For the first two technologies, this prediction has been realized by the placement and successful operation of batteries in RAPS field sites Battery failure is associated mainly with degradation of the positive plate, namely, breakdown/shedding of active material, together with the development of inter-plate short circuits, corrosion/growth of grids, irreversible sulphation (including penetration of separators) Information acquired from the research programme is being used to design advanced RAPS batteries The latter are currently under assessment, both in the laboratory and in RAPS installations

Introduction

Remote-area power-supply (RAPS) systems provide electrical power to isolated homesteads and communities that are denied access to a mains grid. Such facilities also find application in localities serviced by a utility electricity network, but where the required connection and maintenance costs are prohibitive The introduction of RAPS systems that incorporate renewable energy sources assists in the conservation of fossil fuels and helps to protect the environment (e.g , through alleviation of the Greenhouse Effect).

Renewable energy for RAPS systems is generally obtained from photovoltaic (PV) arrays and wind generators. Lead/acid batteries are commonly used to store and deliver the electrical energy derived from these sources The relatively short service life experienced with present-technology batteries is, however, a major impediment to the future advancement of RAPS systems. This limitation is imposed by the complex nature and the rigours of the

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charge/discharge regimes encountered in RAPS operation, and the consequent difficulty in ensuring that the batteries operate under conditions conducive to maximum life performance

A research programme is being conducted in the CSIRO laboratories to obtain a thorough understanding of the extent to which present battery designs meet the requirements of RAPS service The work involves a detailed assessment of a range of batteries under both simulated and field RAPS duties From the data collected, strategies are being devised to overcome the observed shortcomings in battery design, manufacture, and performance, thereby stimulating and accelerating the development of purpose-built RAPS batteries.

Simulation of RAPS service

Simulated RAPS duty profiles have been formulated using insolation levels and load data recorded at RAPS sites around Australia [1, 2]. The derived profiles are termed '7-day' or '1-day', the periods relate to the number of days that elapse before the battery is returned to a full state-of-charge (SOC) Batteries subjected to these profiles are maintained at a constant temperature of 25 °C

The 7-day profile imposes a gradual decrease in SOC to approximately 32% over a period of seven days. On average, the battery is required to deliver about 45% of its nominal capacity per day (note, the accompanying solar energy input results in a higher net SOC) By contrast, batteries are cycled to 26% SOC on the 1-day profile In addition, the 'work' performed per day by the battery is equivalent to approximately 100% of the nominal capacity Thus, the 1-day profile exerts a more strenuous charge/discharge regime on a battery than the 7-day profile. The $C/5$ capacities of batteries under both regimes are determined every four weeks Battery failure is arbitrarily taken as the point at which the $C/5$ capacity has fallen to 75% of the nominal value

As yet, relatively few batteries have been evaluated on the 1-day profile Hence, the following discussion is limited to data obtained under the 7-day profile.

Performance of batteries under simulated RAPS service

The results for batteries operated under the 7-day profile are summarized in Fig 1 It can be seen that flat-plate, flooded-electrolyte batteries, with varying levels of antimony (0–5 wt % Sb) in the positive grid, display widely differing cycle lives This finding is not consistent with the firmly held belief for motive-power (i e , heavy duty) applications that increase in grid antimony content extends cycle life [3]. Thus, the relatively good performance of the antimony-free battery is not readily explained It should be noted, however,

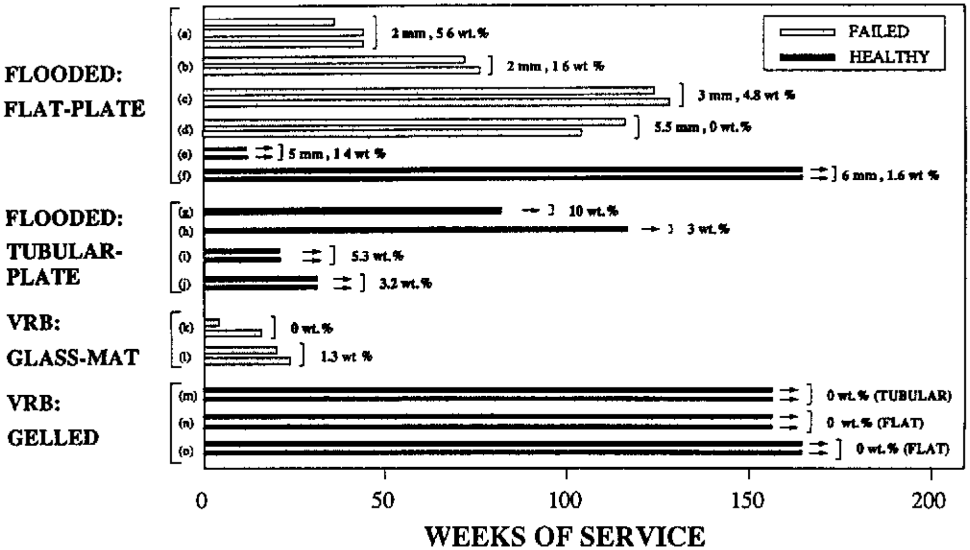

Fig 1 Performance of batteries under 7-day RAPS profile Thickness (mm) and antimony content (wt.%) of positive grids as shown

that both the longest serving battery (with a low antimony grid) and the antimony-free unit have thick positive plates It appears, therefore, that plate thickness is a design parameter that is at least as important as grid antimony content in determining battery cycle life under RAPS duty.

Battery maintenance is also a major issue in RAPS applications Given that access to the systems is often difficult and that users are generally inexperienced in battery management, it is desirable to keep the frequency of water additions to a minimum The rate of water consumption generally decreases with decrease in the antimony content of the positive grid (Fig 2), and since low-antimony batteries have exhibited reliable performance under simulated RAPS service (see above), there are good prospects that water-maintenance requirements can be reduced to a tolerable level during field service

Autopsies of flat-plate, flooded-electrolyte units revealed that losses in capacity were mainly related to degradation of the positive plates (Fig. 3(a)) In particular, softening/shedding of the active material and corrosion/growth of the grids had taken place and, in extreme cases, had given rise to inter-plate short circuits The latter developed across the lower parts of the negative and positive plates following build-up of conductive debris in the base of the container, and/or along the plates' edges as a consequence of 'mossing' — the formation of voluminous deposits at the negative plates through reduction of dispersed positive active material during charging Short circuits were also found to result from 'leading-through' of the separators. In many instances, the positive plates were held together solely by pressure from the adjacent negative plates and separators The use of envelope separation

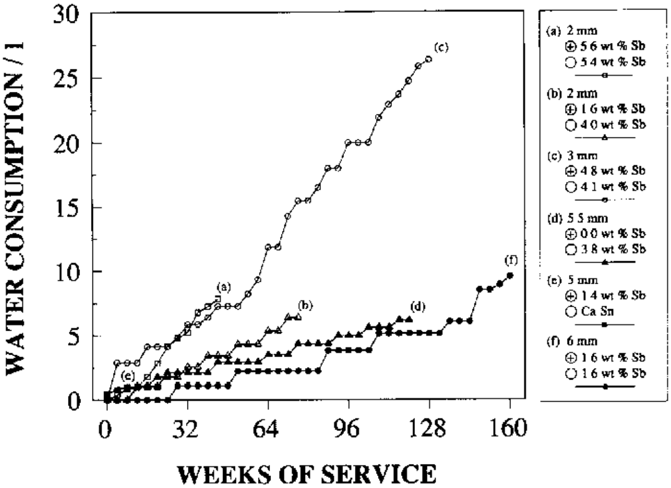

Fig 2 Progressive water consumption of flat-plate, flooded-electrolyte batteries under 7-day RAPS profile

reduced significantly the shedding of positive active material and therefore the incidence of internal short-circuits In a further development, the manufacturer of the batteries yielding the best performance (type (f), Fig 1) has minimized the possibility of mossing by covering the edges and upper parts of the negative plates with plastic guards Degradation processes were generally more acute in batteries with thin positive plates. This reinforces the earlier observation that thick plates are required if batteries are to withstand adequately the stresses imposed by heavy charge/discharge duty

Tubular-plate, flooded-electrolyte batteries possess features that promise good performance under RAPS duty [3] To date, batteries have lived up to this expectation and, except for a few trivial quality-control problems, all units have given trouble-free operation (Fig 1) Corrosive attack of the grids has not been exceptional and has proceeded in a uniform manner (Fig 3(b)). A lowering of the antimony content from the traditional level of ~10 wt % to 3 wt % (due to advances in grid-fabrication procedures) is found to cause a 75% reduction in water consumption under the 7-day profile

Valve-regulated batteries (VRBs) do not require water additions during their normal service life and are therefore particularly attractive for unattended RAPS sites where access is difficult and/or expensive In these batteries, the electrolyte is immobilized by using either an absorptive glass-microfibre separator or a gelled electrolyte With such arrangements, oxygen liberated at the positive plate during charging diffuses readily to the negative plate where it reacts to form lead sulphate and water, thus minimizing water loss The performance of 'maintenance-free' VRBs, using glass-microfibre separation, has been disappointing (Fig 1). The failure mode is associated with heavy and irreversible sulphation of the positive plates From this observation it has become clear that the use of glass-microfibre VRBs in RAPS duties

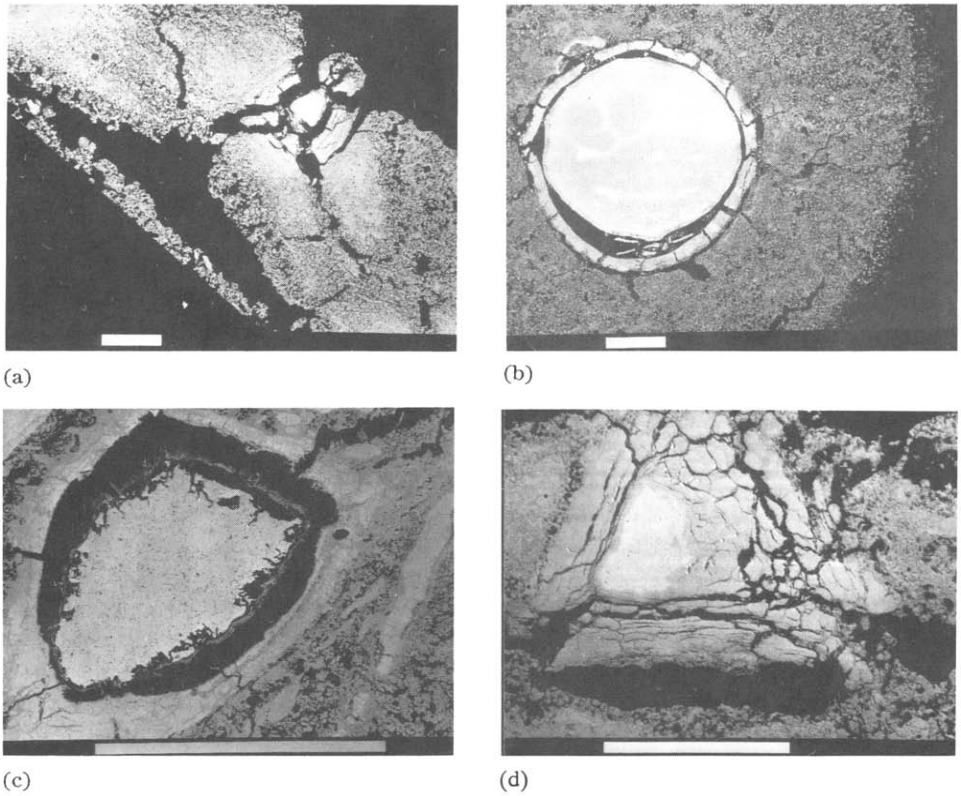

Fig 3 Electron micrographs of polished cross-sections of positive plates from cycled batteries (a) flat-plate, flooded-electrolyte, (b) tubular-plate, flooded-electrolyte, (c) flat-plate, gelled-electrolyte – all under simulated RAPS duty, (d) flat-plate, flooded-electrolyte under RAPS field duty Magnification bar = 1000 μm

requires dedicated charging procedures By contrast, the service of gelled-electrolyte units is, to date, matching that of the best flat-plate, flooded-electrolyte units. Examination after ended periods of service shows that the grids have undergone extensive corrosion with subsequent isolation of the plate material (Fig 3(c)) Reliable operation of gelled-electrolyte batteries under RAPS operation at elevated temperatures (e g., 40–50 °C) has yet to be proved. In addition, careful regulation of the charging regime is required to avoid overcharging If left unabated, the latter will cause drying out of the gel and, thereby, premature failure of the battery.

In summary, the results of laboratory studies using simulated RAPS duty profiles have indicated that certain designs of both flat-plate and tubular-plate, flooded-electrolyte batteries, as well as gelled-electrolyte batteries, are promising candidates for RAPS applications

Performance of batteries in RAPS installations

In addition to the above extensive laboratory programme, the service of batteries in three stand-alone RAPS installations is being monitored. Each site is equipped with a data-logging unit that records all aspects of system operation. In concert with laboratory studies, the criterion for battery failure is 75% of the nominal *C*/5 capacity. Naturally, battery temperature does not remain constant in field service and, under the prevailing conditions, may experience extremes of around 0 °C and 45 °C.

The RAPS site at Talbot, Victoria, is a small family home with a very low average power consumption. The energy is provided mainly by a PV array (144 Wp), with a diesel generator in reserve. The battery bank comprises four, low antimony (1.7 wt.% Sb), flat-plate, flooded-electrolyte, 12 V batteries (100 A h, *C*/5 rate) connected in parallel. A fifth unit allows a battery to be exchanged, in rotation, every three weeks. The *C*/5 capacity of each exchanged battery is determined in the laboratory. The system is equipped with an inverter to provide 240 V a.c.

All batteries in the initial bank failed after 121 weeks of service. Failure was due to intensive corrosion and growth of the positive grids, combined with general degradation of the accompanying active material (Fig. 3(d)). In all cases, the positive plates had bulged and expanded within the plane of the plates to such an extent that fracture had taken place at the top of the grids. This was so severe in three of the batteries that short-circuits had developed between the negative busbar and the fractured top members of the positive grids. The positive material was generally very soft and 'muddy'; it was held together only by the separator envelopes. Similar modes of failure under RAPS conditions have been observed by other workers [4].

The RAPS system at Elphinstone, Victoria, is significantly larger than that at Talbot, with an average power consumption of approximately 1 kW h/day. Power at both 12 V d.c. (6 batteries) and 24 V d.c./240 V a.c. (16 batteries) power is available. Tubular-plate, flooded-electrolyte batteries utilizing granular oxide [5] are currently being evaluated; the performance to date is summarized in Fig. 4. Battery capacities are determined using a rotational schedule similar to that instigated at Talbot. The performance of the batteries is most promising. For the first 25 weeks of service, the capacities were approximately equal to the nominal value. After this period, however, there was a general decline in the condition of the battery bank. This coincided with the onset of winter. Moreover, the insolation levels were well below the average expected for that time of year. The situation was further exacerbated by problems with the battery charge regulator. Despite these difficulties, most of the capacity loss experienced during the first winter of operation was recovered in the following spring/summer seasons. For example, one battery registered a capacity that was just below the cut-off limit in mid-winter (36 weeks of service) but, over a year later, the performance returned to almost the nominal level. This type of behaviour suggests that a 'memory effect' is operative. Indeed, there is evidence [6] that the capacity of lead/

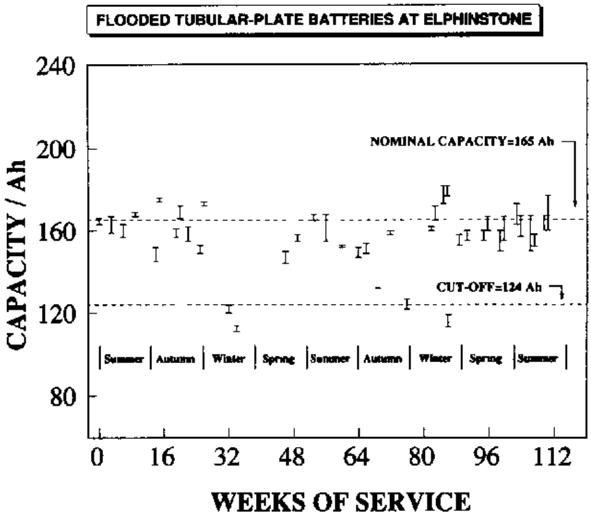

Fig 4 Performance of tubular-plate batteries using granular oxide at Elphinstone RAPS site

acid batteries can be influenced by the previous charge/discharge history.

The RAPS facility on French Island, Victoria, provides power to a tourist lodge [7]. The average load on the system is approximately 20 kW h/day, but daily peak usages of 50 kW h have been experienced The energy is supplied by a PV array, a wind generator, and a diesel generator. The battery bank consists of forty, 6 V, flat-plate, flooded-electrolyte batteries connected in series, with an inverter to convert 240 V d c. to 240 V a.c. The first battery bank was retired in mid-1988, and suffered from failure modes similar to those witnessed at Talbot, i.e , severe degradation of the positive plates The replacement batteries comprise a set of purpose-built, flat-plate, flooded-electrolyte units (see below). These have given trouble-free operation for the past two years

The above failure modes exhibited by batteries undergoing service in RAPS systems are very similar to those experienced during laboratory evaluations of performance This confirms that the 7-day test regime is an effective simulation of RAPS field duty

Purpose-built batteries for RAPS applications

An important outcome of the research conducted at CSIRO is the development of purpose-built RAPS batteries. This is achieved by combining the results emanating from the above work programme with progress made in other in-house projects that are aimed at improving various aspects of lead/acid battery technology.

In collaboration with a battery manufacturer, CSIRO is evaluating different components and process parameters for flat-plate, flooded-electrolyte RAPS batteries [8] These include various grid alloy combinations, as well as two extremes of curing conditions, namely, high-temperature/high-humidity and low-temperature/high-humidity All other design variables (e g., plate thickness, paste density, etc) are kept constant This is achieved by first pasting (to a fixed thickness and weight) a range of positive and negative plates that differ only in grid alloy composition, i e , positive 1 7 or 5 0 wt % Sb, negative 1 7 or 5 5 wt % Sb, or lead–calcium. Samples of each type of plate are then exposed to the different curing conditions Finally, the plates are assembled into batteries and subjected to the same formation procedure

The batteries are being evaluated under the 7-day RAPS profile. An initial sharp decline in capacity was exhibited by batteries using lead–calcium negatives Remarkably, the situation improved after about 12 weeks of operation and the capacities are still well above the cut-off limit at the present service life of 64 weeks The best capacity performance has been exhibited by batteries containing a high antimony content in both the positive and negative grids after 80 weeks, the capacity is stable and very close to the nominal value This is encouraging as the batteries are of similar design to the former type (a) units that failed within 50 weeks (see Fig. 1) It is also noteworthy that the high-antimony batteries are giving satisfactory field performance in the RAPS system at French Island These results demonstrate that significant improvements in battery reliability can be achieved through exercising more rigorous control of the plate-processing stages

With all other parameters equal, water consumption was found (as expected) to increase with increase in the antimony content of the positive grid (Fig 5) The influence of cured-plate phase chemistry was, however, quite remarkable Batteries assembled with positive plates cured under low-temperature conditions, favouring the formation of tribasic lead sulphate

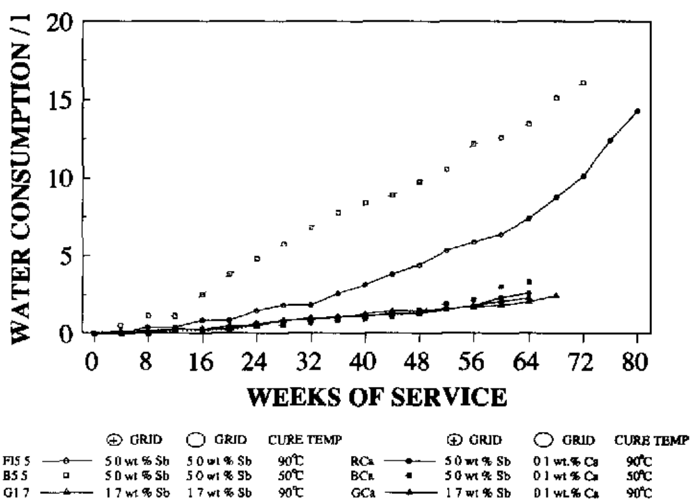

Fig 5 Progressive water consumption of purpose-built, RAPS batteries (flat-plate, flooded-electrolyte) under 7-day RAPS profile

($3PbO\ PbSO_4\ H_2O = 3BS$), were found to consume more water than those using plates cured at high-temperature, which promotes the development of tetrabasic lead sulphate ($4PbO\ PbSO_4 = 4BS$), see Fig. 5. Differences in the distribution of antimony within the two types of battery may provide an explanation for this diversity of behaviour It has been shown [9] that soluble antimony (produced via corrosion of the grid) is strongly adsorbed by lead dioxide, but only weakly by lead sulphate During cycling, therefore, the positive plate will adsorb and desorb antimony during the charge and discharge regimes, respectively Further, it has been suggested [10] that this adsorption/desorption process can decrease the rate of antimony poisoning of the negative plate and, consequently, the extent of hydrogen evolution, i.e , water loss It is therefore possible that 4BS-rich material generates a formed-plate structure that hinders the rate of release of antimony relative to that experienced with 3BS plates This hypothesis is being examined further in our laboratories

Conclusions

The above work seeks to optimize the performance of lead/acid batteries for RAPS duty It should be remembered, that RAPS batteries are required to serve under relatively demanding conditions. For example, the batteries must be able to withstand the stresses of repeated charge/discharge cycles to a low SOC (with widely varying charge and discharge rates) and may also be forced to remain at this low SOC for extended periods of time In addition, such operations should be achieved with minimum water loss Remedies to overcome the present shortfall in desired performance involve a combination of more resilient battery components, more sophisticated regulation of battery charge/discharge operations, and further implementation of strategies to minimize water-maintenance requirements. It has been acknowledged [11] that research of the type reported here is encouraging battery manufacturers to face these challenges

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