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ADVANCED LEAD/ACID BATTERIES FOR STAND-ALONE POWER-SUPPLY SYSTEMS

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Introduction

The number of domestic stand-alone power-supply systems operating in the Asia–Pacific region is growing dramatically. This situation is largely attributable to the greater import now attached to the exploitation of renewable energy sources (solar, wind, etc.) and, in turn, to the improvements being made in devices and management systems for efficiently harnessing these sources. The photovoltaic conversion of solar energy is the most common means of generating electrical power. By comparison, the use of wind-driven generators is less widespread and is generally restricted to coastal areas. In both approaches, the stochastic nature of the energy availability requires the provision of some form of energy storage in order to guarantee a continuous supply of electrical power. This role is usually filled by a bank of rechargeable batteries with the lead/acid type being favoured, mainly on the grounds of cost and familiarity. A generator set (petrol- or diesel-fuelled) may also be necessary: either to charge the batteries during extended periods of adverse weather conditions, or to meet heavy loads. Figure 1 shows the layout of a typical stand-alone power supply. The most common application of such a facility is in areas that are remote from the mains electricity network, and where connection to the grid is prohibitively expensive. It has become commonplace to use the acronym 'RAPS' (remote area power supply) to denote such installations.

Despite being the popular choice for energy storage, there are problems associated with the employment of lead/acid batteries. Most of these stem from the rigours of the complex charge/discharge cycling regimes experienced in RAPS operations through the action of factors such as the wide variability in power demand within/between sites, daily/seasonal changes in climatic conditions (*i.e.*, energy input), etc. The perception of these problems, together with the pressing need for a more reliable and longer-lived lead/acid battery, has stimulated a major research programme in CSIRO involving the following activities.

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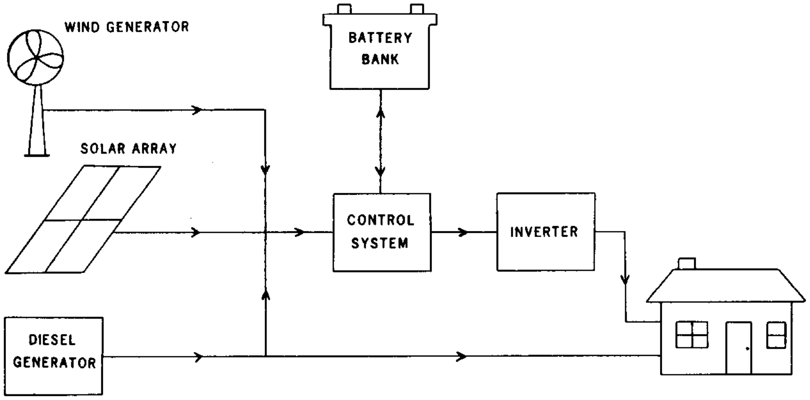

Fig. 1. Schematic diagram of a typical stand-alone power-supply system.

- Evaluation of state-of-the-art lead/acid battery technology under simulated RAPS duty
- Identification and correction of battery failure modes specific to RAPS operations
- Incorporation of results into the development and construction of purpose-built RAPS batteries (in conjunction with major battery manufacturers)
- Monitoring of battery performance and all electrical transfers at various domestic RAPS sites
- Field trials of advanced batteries in RAPS systems

This paper summarizes the results obtained to date in each of the above areas.

Evaluation of lead/acid technology: cycle life and failure modes

Lead/acid technologies can be classified according to:

(i) the positive-plate type, *i.e.*, tubular or flat-pasted;

(ii) the positive grid-alloy composition, *e.g.*, antimony content;

(iii) the electrolyte state, *i.e.*, flooded or immobilized.

Given this wide variability in design, there is a clear need to identify those features that are the most suitable for RAPS service. Accordingly, CSIRO has instituted a detailed programme of evaluation in which representative examples of each battery type are subjected to simulated RAPS duty in the form of controlled charge/discharge sequences. The latter have been derived from consideration of the energy input/demand profiles experienced by typical solar array/diesel generator/battery hybrid systems in meeting the power needs of an average-sized family household [1]. At present, two different profiles are being used under which charge/discharge cycling proceeds for either 7 days or 1 day prior to returning the battery to full charge; these are

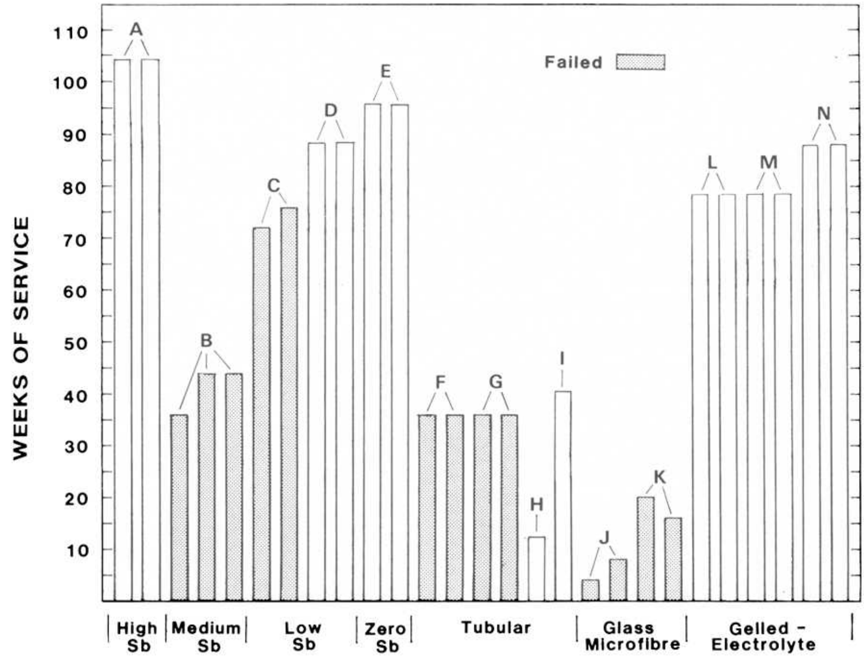

Fig. 2. Battery performance under simulated RAPS service (7-day profile). Letter refers to brand of battery.

termed the '7-day' and the '1-day' profiles, respectively [2]. Battery condition is monitored by conducting capacity ($C/5$) tests at regular intervals ($\sim$4 weeks). The end of useful battery life is taken as the point at which the capacity falls below 75% of the value determined initially. A summary of the results obtained to date for batteries cycled under the 7-day profile is given in Fig. 2.

Flooded-electrolyte batteries

With half the number of batteries placed on trial having failed, some interesting trends are emerging. Among the flooded types, there appears to be little relationship between grid antimony content and cycle life. For example, all three brand B batteries (3.0 wt.% Sb) have failed, as have the two brand C units (1.7 wt.% Sb). By contrast, batteries at the extremes of the antimony spectrum are still giving good service. (Note, the difference in the weeks-of-service achieved to date by the various healthy batteries reflects a staggering in the commencement of the cycling tests.) The leading performance of brand A batteries is in line with the general expectation for units having a high antimony content in the positive grid, *i.e.*, >5 wt.%. On the same basis, however, the impressive showing of brand E batteries (pure-lead positive grids) is not readily explained. It should be remembered, however, that plate thickness is also a determinant of battery life. The plates in all of the failed units are considerably thinner than those in most of the surviving examples. This suggests that the benefits of thick plates in cycling applications are at least as important as those related to antimony content. Given that the pure-lead positive type under examination has antimonial (5.5 wt.% Sb) negative grids, some antimony could be transferred during cycling to the positive plates [3]; this possibility will be investigated during *post mortem* examinations.

Autopsies on failed thin-plate batteries have shown that the decline in performance is mainly due to degradation of the positive plates. This is manifested as extensive grid corrosion and mutual isolation of the constituent particles of the active material. In many cases, the aged positive plates are held together solely by pressure from the adjacent negatives and separators in the plate group. These observations show that the service lives of thin-plate batteries are limited by the mechanical stresses of charge/discharge duty. Surprisingly, all of the failed units are negative-limited designs; this is expected to mitigate the processes that cause positive-plate degradation.

Tubular-plate batteries

Of the five tubular-plate batteries placed on trial, four failed after 36 weeks of service. Since many operational features of tubular-plate batteries [4] suggest that this design should excel in typical RAPS service, the results obtained to date under simulated duty have been disappointing. The cause(s) of this poor performance has been difficult to ascertain, although the failure mode in each of the two brand F batteries has been attributed to an easily avoidable fabrication defect in one of the cells.

Sealed batteries

Several designs of sealed batteries employing recombinant electrolyte technology are under examination. Those with absorptive glass-microfibre separation failed after only short periods of operation. Autopsies revealed heavy and irreversible sulphation of the positive plates. In marked contrast, batteries employing gelled electrolyte have proved to be far superior and promise excellent service.

Advanced lead/acid battery design

An important stage in the research programme involves the incorporation of results from the above battery evaluation schedule, along with advances in lead/acid technology, into the design and construction of purpose-built RAPS batteries. To this end, CSIRO is currently seeking improvements in both tubular-plate and flat-plate batteries.

The advancement of tubular-plate batteries involves the use of a granular form of battery oxide [5]. This oxide is manufactured by Cookson Industrial Materials Ltd. from a proprietary 'special grade' oxide using only sulphuric acid as a binder. The resulting material is composed mainly of spherical particles (~80% fall within the size range 125 - 1500 μm). By comparison, a typical Barton-pot oxide consists of much smaller particles (95% are less than 20 μm). On account of its large particle size, granular oxide is free-flowing and non-dusting. These features allow rapid and hygienic filling of tubular plates. In addition, acid ingress into the plates is good and raises the initial capacity. The behaviour under charge/discharge cycling is equally impressive. Tests on tubular-plate cells (216 A h, *C*/5) produced by CBS Batteries Ltd. show that those with granular oxide match the performance of equivalent cells prepared from a standard red lead/leady oxide blend. Both variants are giving excellent service after 1500 cycles under the BS 2550 schedule (*i.e.*, capacity >90% of nominal value). CBS Batteries has provided CSIRO with 30 examples of their Model 6RA200, granular oxide battery (200 A h, *C*/10) for evaluation under RAPS conditions. Most of the units have been installed at one of the RAPS sites being monitored (see below), while the remainder are being cycled in the laboratory under both the 7-day and the 1-day profiles.

The second development in the area of advanced battery design centres on a range of flat-plate batteries being produced by GNB Australia Ltd. These are based on a standard motive-power type and incorporate many of the CSIRO findings gained from extensive studies into the maximization of cycle life under deep-discharge conditions [6, 7]. Thus, manufacturing parameters and specifications have been ‘fine tuned’ to give optimum performance under RAPS conditions. The product range includes a number of different grid alloys and two types of curing procedure. Some of the batteries have been installed at a RAPS site for field evaluation (see below), while the remainder are being subjected to simulated duty profiles.

Monitoring of stand-alone power-supply systems

As well as evaluating lead/acid batteries in the laboratory, strategies are in place to monitor the functioning of different types in fully-operational, domestic RAPS systems. Details of the sites included in the programme are given in Table 1.

A data-logging system is installed at each site to maintain a record of all electrical transfers. From the compiled information, it is planned to formulate a detailed profile of the behaviour of each component in the RAPS system. This analysis will be used to assess and refine the simulation of RAPS service for investigation of battery performance in the laboratory. In addition, comparison of operational characteristics between sites will allow a study to be made of the effects of RAPS system architecture on the energy storage component.

At the Talbot site, a microprocessor-based logger records all aspects of system operation at 30 min intervals. The data are collected over a period of three weeks, after which down-loading to disk storage is carried out with a

TABLE 1

Monitored RAPS sites in Victoria, Australia

Location	Description	Energy source	System voltage	Configuration[a]
Talbot	Family home	PV array	12 V d.c./240 V a.c.	(1 × 12 V) × 4
Elphinstone	Family home	PV array	12 V d.c.	(2 × 6 V) × 3
			24 V d.c./240 V a.c.	(4 × 6 V) × 4
French Island	Tourist lodge	PV array/wind/ diesel	240 V d.c./240 V a.c.	(40 × 6 V)

[a] (No. of modules in series × module voltage) × no. of strings in parallel.

portable computer. At the same time, one of the four batteries is taken back to the CSIRO laboratories for determination of capacity. As with the batteries being evaluated in the laboratory, units undergoing field duty are deemed to have failed when the capacity ($C/5$) has fallen to 75% of the initial value. Five commercially-available batteries (123 A h, $C/20$) are used at Talbot on rotation so that each unit spends 3 of every 15 weeks out of the system. Performance to date is shown in Fig. 3.

The Elphinstone system offers the flexibility of power at 12 V d.c. or 240 V a.c. In December, 1988, the original battery bank was replaced by a set of Model 6RA200 tubular-plate modules supplied by CBS Batteries Ltd. The capacity of these units is being closely tracked under a rotation schedule similar to that adopted at Talbot. In parallel with the field trial, two units are

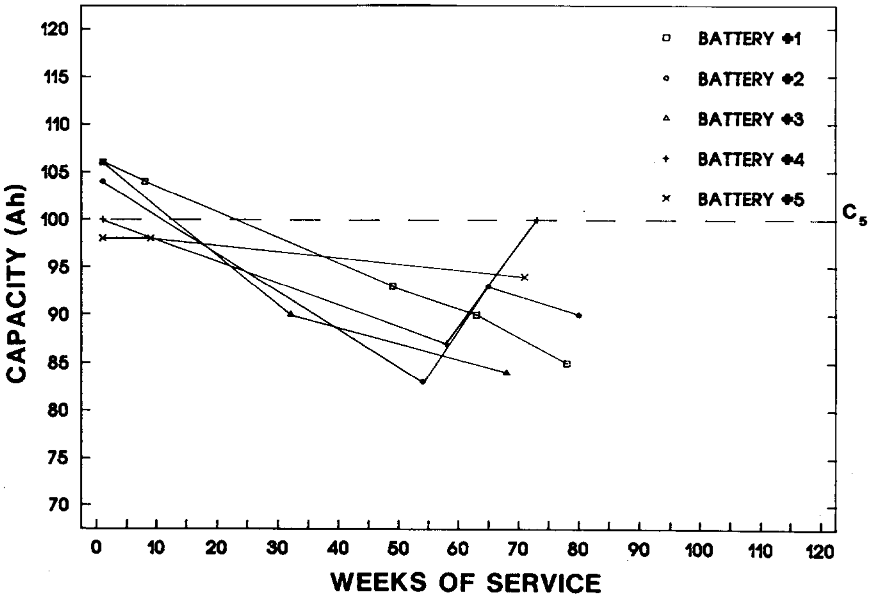

Fig. 3. $C/5$ capacity of batteries after periods of operation at the Talbot RAPS site.

undergoing charge/discharge cycling in the laboratory (7- and 1-day RAPS profiles). This type of comparative study is essential to the further development of 'standard' life-cycle regimes for evaluating new RAPS battery technology.

French Island Lodge is a tourist facility that is capable of accommodating up to 20 people. The power supply must therefore cope with an electrical load that is much larger than those at Talbot and Elphinstone. To minimize the problems associated with such high loads, the battery bank has been configured at 240 V d.c. This arrangement results in low d.c. currents and high inverter efficiency. The batteries in place at the Lodge are the above-mentioned advanced flat-plate design produced by GNB Australia Ltd. in collaboration with CSIRO. Capacity is recorded at approximately two-monthly intervals. Detailed logging of all system operation parameters is being carried out by the Victorian Solar Energy Council. Two batteries are also being subjected to duty under simulated RAPS profiles.

Concluding comments

Batteries providing energy storage in RAPS systems must fulfil a number of important requirements. In particular, the ideal RAPS battery should be able to withstand repeated deep-discharge cycling, while requiring minimal attention in the way of water addition and general maintenance. A design that embodies all of these criteria has hitherto proved difficult to develop. Nevertheless, there remain many aspects of the manufacture and operation of the lead/acid system that can be refined to give longer service life under RAPS conditions. The work reported here is the first stage of a dedicated effort towards identifying such factors and assisting the growth and development of a new and potentially enormous market for lead/acid batteries.

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References

1 R. B. Zmood, T. A. McCluskey, D. A. J. Rand, W. G. A. Baldsing and R. J. Hill, in A. R. Langrebe, D. A. J. Rand, S. L. van Voorkees and R. K. Sen (eds). *Proc. Symp. Stationary Energy Storage: Load Leveling and Remote Applications*, Proc. Vol. 88-11, The Electrochemical Society Inc., Pennington, NJ, 1988, pp. 375 - 393.

2 D. A. J. Rand and W. G. A. Baldsing, *J. Power Sources, 23* (1988) 233 - 244.
3 J. L. Dawson, M. I. Gillibrand and J. Wilkinson, in D. H. Collins (ed.), *Power Sources 3,* Oriel Press, Newcastle upon Tyne, 1971, pp. 1 - 12.
4 D. Pavlov, in B. D. McNicol and D. A. J. Rand (eds.), *Power Sources for Electric Vehicles,* Elsevier, Amsterdam, 1984, pp. 219 - 221.
5 M. J. Weighall, D. W. H. Lambert, D. A. J. Rand and W. G. A. Baldsing, in T. Keily and B. W. Baxter (eds.), *Power Sources 12,* International Power Sources Symposium Committee, Leatherhead, U.K., 1989, pp. 77 - 91.
6 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. April, 1988),* CSIRO Division of Mineral Chemistry, Melb., Commun. MCC 837, April, 1988, 105 pp.
7 D. A. J. Rand, *The Battery Man,* October (1987) 12 - 18.