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TUBULAR-PLATE LEAD/ACID BATTERIES FOR REMOTE-AREA ENERGY STORAGE

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Introduction

Initial research on electrochemical storage cells began on the lead/acid, nickel/cadmium and nickel/iron systems during the latter half of the last century. Since then, however, many new battery systems have been discovered. Over the decades, the lead/acid cell/battery has been developed into a highly efficient, safe and reliable energy storage device and is now the most widely employed of all known systems.

Uses for lead/acid batteries are numerous and diverse and have resulted in various application-specific designs, ranging in size from a few to tens-of-thousands of ampere-hours. Irrespective of the service to be performed, the major criteria in selecting the best battery for a given application remain the same [1].

In remote-area power-supply (RAPS) applications, particularly with photovoltaic (PV) and PV-hybrid systems, the energy storage component must have the following characteristics:

- low self-discharge
- good reliability under cyclic discharge conditions
- long maintenance interval
- high charging efficiency
- wide operating temperature
- robust design
- high cost-effectiveness
- manufactured under stringent quality controls

Conventional flat-, Planté- and/or tubular-plate stationary and motive-power cell designs have all been used in RAPS applications. The different battery types meet some of the above criteria, *e.g.*, long maintenance intervals, high charge efficiency and a wide range of operating temperature. The other requirements are often, however, neither met nor achieved by overdesign.

As a result of the above deficiencies in performance of lead/acid RAPS batteries, a rigorous research and development programme has resulted in an optimised, advanced tubular-plate design that fulfils all the requirements.

0378-7753/89/$3.50

This is the 'Ra-Power' remote-area energy-storage cell/battery range marketed by CBS Batteries Limited.

Optimised cell design for RAPS applications

The corrosion characteristics of tubular-plate electrodes under simulated stationary (continuous anodic polarisation) and motive power (cyclic anodic/cathodic polarisation) conditions are shown in Fig. 1 [2]. The conclusions, made by Rogachev *et al.*, that pure lead and low antimony–lead alloys are preferred for tubular stationary batteries, whereas high antimony–lead alloys are better for tubular traction types, appear to provide the basis for alloy selection for tubular-plate RAPS batteries. In the latter application, the duty cycles are more akin to a cyclic charge/discharge regime than to a continuous anodic polarisation (float charge).

Grid alloy corrosion, whilst a significant possible contributor in a design FMEA (failure mode and effects analysis) of a tubular-plate, cannot be taken in isolation. Other factors such as alloy creep resistance, plate geometry, active material formulation, plate processing and subsequent active material morphology, separator material, electrolyte operating density/stratification effects, and water loss must also be considered when drawing up the total material specification of the optimised lead/acid RAPS cell/battery.

The positive grid alloy must be highly resistant to creep [3], owing to the stresses applied to the grid structure by the PbO_2 corrosion layer that develops during charge/discharge cycling [4]. Alloy composition, grid design, and grid fabrication technique all play a significant part in determining the final grid microstructure, and hence the creep resistance. For example, the beneficial effects of small additions of arsenic (~0.15 wt.%) to low-antimony (<3 wt.%) alloys are well documented [5].

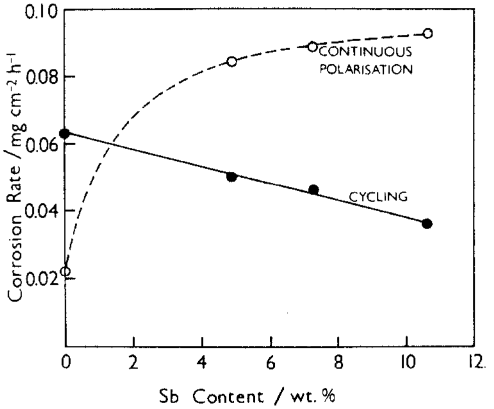

Fig. 1. Dependence of corrosion rate on the antimony content of the alloy [2].

Apart from serving to strengthen the grid metal, antimony (through dissolution from the positive grid) exerts beneficial effects on the mechanical stability of the active material mass, the particle morphology, and the adherence of active material to the grid [6 - 9]. On the deficit side, diffusion of antimony through the electrolyte and subsequent deposition on the negative electrode result in a lowering of the hydrogen overpotential and, consequently, to increased hydrogen evolution during both battery charge and on open-circuit stand [10]. The antimony content of the positive grid alloy must therefore be reduced to minimise self-discharge and water-loss effects, yet still be sufficient to ensure adequate service life. Studies of commercial, flat-plate lead/acid batteries under cycling conditions suggest [11] that a minimum of 1.5 wt.% antimony is required in the positive grid.

The superior reliability, performance and energy efficiency of tubular-plate lead/acid cells in cyclic applications is well known [12, 13]. The initial capacity and cycle-life characteristics of tubular-plate motive-power cells have been improved by the use of advanced plate designs and materials [14]. The increased utilisation of the active mass in the latter has been achieved by the development of a granular form of blended 'battery oxide' (GBO). The GBO is composed mainly of spherical particles, with ~80 wt.% falling within the size range: 125 - 1500 μm, Fig. 2. The large mean particle size aids acid ingress into the plates and raises the initial capacity above values encountered with conventional oxides. In summary, the advanced tubular-plates enhance the performance, durability and reliability of the 'Ra-Power' lead/acid RAPS cell through the following inherent properties:

- greater mechanical stability
- improved active mass utilisation
- reduced grid corrosion
- superior active material/grid weight ratio

Comparison of flat-plate and tubular-plate capacity

The discharge performance characteristics of 'Ra-Power' type 2Ra455 cells (Table 1) have been compared with a state-of-the-art equivalent rated capacity, flat-plate RAPS cell. At the $C/120$ discharge rate, both types of cell have similar ampere-hour capacities, although the flat-plate cells have a much lower watt-hour capacity (Table 2). At higher discharge rates ($C/10$ and $C/5$), however, the advanced tubular-plate designs out-perform their flat-plate counterparts, both in A h and W h capacity. The discharge voltage characteristics are shown in Fig. 3.

These results emphasise the effectiveness of tubular-plate designs in improving the active material utilisation of the positive plate. The inferior performance of the flat-plate design is the result of resistance polarisation and diffusion polarisation during discharge. As would be expected, the former effects are more pronounced at high rates of discharge, while the diffusion polarisation effects exert less influence at longer discharge times.

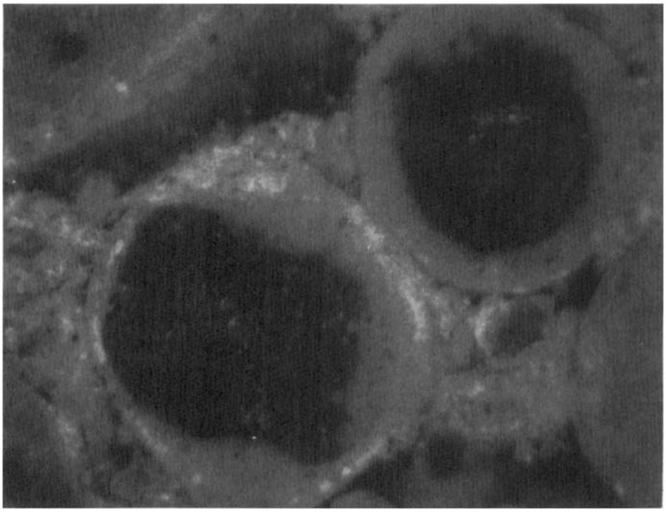

Fig. 2. Optical micrograph of granular oxide, ×135 [14].

TABLE 1

Ra-Power tubular-plate remote-area power-supply cell/battery specifications

Type	Volts (V)	Capacity (A h)[a]			Dimensions (mm)			Weight (kg)[b]	
		$C/10$	$C/20$	$C/120$	L	W	H	dry	wet
6Ra200P	6	200	220	250	264	184	280	23.7	30.9
12Ra120P	12	120	130	150	345	173	300	28.8	37.8
12Ra40	12	40	45	55	272	205	379	25.6	35.6
12Ra80	12	80	95	110	380	205	379	37.2	53.3
12Ra120	12	120	140	165	380	205	379	48.1	60.8
6Ra160	6	160	190	220	272	205	379	30.6	39.9
6Ra240	6	240	285	330	380	205	379	46.0	59.5
2Ra160	2	160	190	220	103	206	379	11.6	15.8
2Ra325	2	325	385	445	124	206	500	16.2	24.4
2Ra390	2	390	460	535	145	206	500	21.2	32.7
2Ra455	2	465	540	625	166	206	500	23.5	34.5
2Ra595	2	595	700	820	191	210	675	29.0	48.0
2Ra680	2	680	800	935	191	210	675	32.3	50.8
2Ra765	2	765	900	1050	233	210	675	35.2	53.2
2Ra850	2	850	1000	1170	233	210	675	39.6	62.7

[a] Capacities measured at 25 °C to 1.80 V/cell, top-of-charge acid sp.gr. 1.240 ± 0.01 at 20 °C.

[b] Cell/battery weights are subject to ±5% tolerance.

Diffusion polarisation effects relate to the mass-transfer processes (transport of species to, and from, reaction sites) required to maintain a flow of current and are influenced by:

TABLE 2

Capacity and energy performance comparison of tubular- and flat-plate lead/acid RAPS cells

Discharge		Capacity (A h)		Energy (W h)	
Rate	Current (A)	Tubular	Flat	Tubular	Flat
~*C*/120	5.6	627	607	1240	1185
~*C*/10	38.5	486	362	905	700
~*C*/5	80.0	386	251	735	475

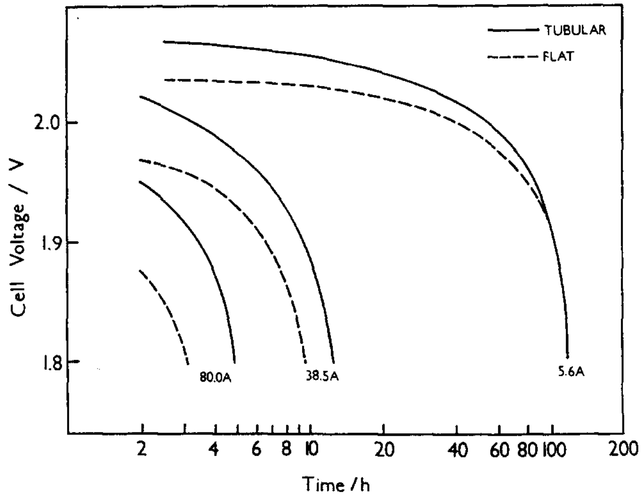

Fig. 3. Comparison of tubular- and flat-plate discharge voltage/time characteristics.

- convection and stirring of the electrolyte
- electrolyte concentration (specific gravity)
- positive-plate geometry

The resistance polarisation effects, on the other hand, are 'internal resistance' ohmic losses and are a function of the cell/battery design.

Advanced tubular-plate reliability/durability

The service life of a lead/acid cell/battery under cyclic polarisation conditions is generally limited by the performance of the positive plate, the capacity of which gradually declines. This mode of failure is common to both tubular-plate and flat-plate battery designs and the loss of capacity has been attributed [15] to the following mechanisms:

- active material morphology change
- shedding of material
- sulphation effects
- plate growth
- grid corrosion

It is now generally accepted that the phase composition and morphological structure of the positive active material is strongly dependent upon the processing conditions and both the nature and composition of the precursor oxides [16]. The optimum phase composition for flat-plate, deep-cycle batteries has been found to correspond to an α-PbO_2:β-PbO_2 weight ratio of ~0.8 after initial plate formation [17]. The quantitative determination of battery-plate composition, using X-ray diffraction techniques, has only recently been made 'user-friendly' by the development of the PEAKS software package [18]. This technique is capable of identifying the 11 phases that are commonly encountered in battery plates, *i.e.*, Pb, α-PbO, β-PbO, Pb_3O_4, $2PbCO_3 \cdot Pb(OH)_2$, $PbSO_4$, $PbO \cdot PbSO_4$, $3PbO \cdot PbSO_4 \cdot H_2O$, $4PbO \cdot PbSO_4$, α-PbO_2 and β-PbO_2.

Cycle-life endurance testing, carried out on motive-power cells (9-plate; 216 A h, *C*/5) in the CBS Battery Test Laboratory, has proved the reliability

TABLE 3

Laboratory performance of tubular-plate motive-power cells under BS2550 procedure

Cycle no.	Capacity (*C*/5 rate, % nominal value)	
	Granular oxide[a]	Standard oxide[a]
1	118	85
3	114	100
10	120	110
50	120	112
102	108	109
150	112	111
200	103	104
300	105	106
400	102	104
500	105	104
600	104	105
700	92	98
800	93	99
900	97	101
1000	91	94
1050	94	94
1101	94	98
1150	94	99
1200	95	99
1250	94	96

[a] Two cells of each type tested, results are average values.

of the advanced tubular-plates [14]. In these tests, the cells were subjected to the BS2550 test procedure [19]; the results are given in Table 3. In addition, CBS Batteries Limited has provided CSIRO, Australia, with forty Type 6Ra200 (Table 1) batteries for evaluation under RAPS duties. This forms part of a major research project into the development of lead/acid batteries for use in remote-area domestic-power supplies, sponsored by the Australian National Energy Research, Development and Demonstration Council (NERDDC) [20]. The 6Ra200 batteries are being tested both under simulated RAPS conditions in the CSIRO laboratories and in service at a domestic stand-alone PV installation at Elphinstone, Victoria [21]. In the laboratory, the batteries are operated under two different battery load–current profiles, namely, the RAPS '7-day' [20] and '1-day' [22] charge/discharge sequences, Figs. 4 and 5. Battery condition is monitored by conducting *C*/5 capacity tests at ~4 week intervals. The end of useful battery life is taken as the point at which the capacity falls to below 75% of the value determined after commissioning. The condition of the batteries

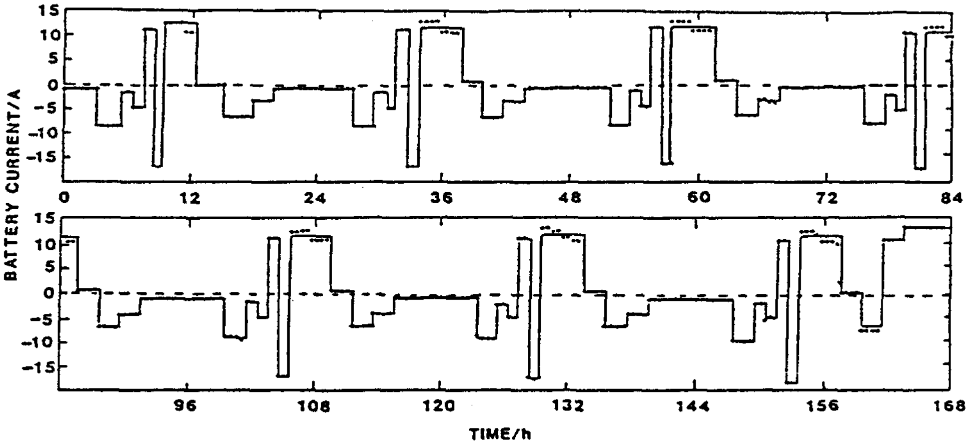

Fig. 4. Seven-day profile for testing batteries under simulated RAPS service [20].

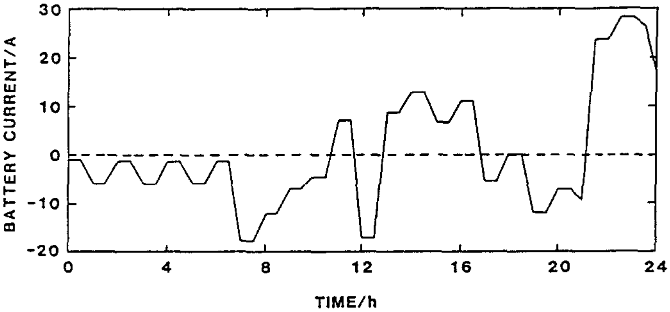

Fig. 5. One-day profile for testing batteries under simulated RAPS service [22].

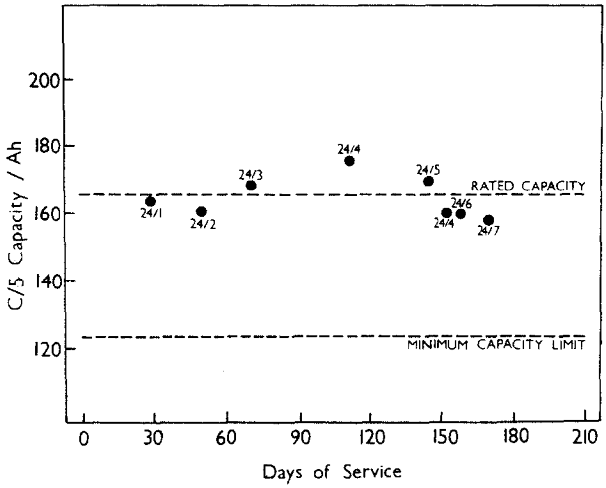

Fig. 6. In-service capacity of 6Ra200 batteries at Elphinstone RAPS site.

in the field is determined by periodically (~3 weeks) returning the batteries to the laboratory for $C/5$ capacity testing.

To date, the 6Ra200 batteries have completed 30 weeks under the 7-day RAPS profile and over 170 days in service at Elphinstone. The $C/5$ capacities of the batteries after periods of operation in the 24-V system at the Elphinstone RAPS site are shown in Fig. 6.

Cost-effectiveness

The following power system designs have been considered for remote-site telecommunications applications in two distinct geographic locations, namely, coastal regions above latitude 50N and inland equatorial regions:

- diesel engine generator
- thermal electric generator
- closed-cycle vapour turbine
- photovoltaic (PV)
- wind turbine
- PV-hybrid (PV–diesel)
- wind-hybrid (wind–diesel)
- solar and wind-hybrid

The economics of these power systems have been analysed in detail [23]. It has been found that in both geographic regions, PV, wind and their associated hybrid systems are the most cost-effective energy generation and storage options. The results are summarised in Table 4.

TABLE 4

Cost summary of eight commonly used power systems for remote locations [23]

System	Cost ($/kW h)	
	Region 1	Region 2
Diesel engine generator	1.53	1.53
Thermal electric generator	2.02	2.02
Closed-cycle vapour turbine	1.61	1.61
Photovoltaic (PV)	0.99	0.46
Wind turbine	0.76	0.44
PV–diesel hybrid	0.99	0.73
Wind–diesel hybrid	0.95	0.87
Solar + wind-hybrid	0.88	0.58

In 1984, the cost of the lead/acid battery compared favourably with other secondary batteries, *e.g.*, nickel/cadmium and nickel/iron [24]. Five years later, the lead/acid battery is still the lowest cost energy-storage system and, moreover, its price has decreased significantly:

- ~0.25 $/W h (1984)
- ~0.10 $/W h (1989, CBS 'Ra-Power' range)

This overall cost reduction is attributable to effective 'cost engineering' during the design of the 'Ra-Power' range, combined with labour-efficient manufacturing techniques and the improved energy efficiency of the advanced tubular-plate designs.

Quality and design

Disciplined design control at the conceptual stage of any project is an essential requirement in order to ensure that the customer is supplied with a quality product that is fit for its purpose. The International Organisation for Standardisation (ISO) details the systems control requirements for all aspects of the design, specification, manufacture and marketing of a product by a company. These requirements are set down in the ISO 9000 series of Quality Management System Specifications [25]. The relative importance of critical product features and customer requirements for flooded, tubular-plate RAPS batteries are shown in the correlation matrix [26] given in Fig. 7. All 'Ra-Power' cells/batteries are manufactured under the control of a Quality Management System that meets these exacting ISO requirements.

CRITICAL PRODUCT FEATURES / CUSTOMER REQUIREMENTS	POSITIVE PLATE	NEGATIVE PLATE	SEPERATOR	ELECTROLYTE	BATTERY CONTAINER	CONTAINER TO COVER SEALS	POST SEALS	VENT / FLAME ARRESTOR	BATTERY SYSTEM	TERMINALS / CONNECTORS
ENERGY DENSITY	●	◑		◑	○					○
LIFE	●	◑	◑	◑	○	◑	◑	○	○	○
WEIGHT	●	●		◑	◑					○
SAFETY				◑	●	●	●	●	●	●
RELIABILITY	●	◑	◑	◑	○	●	●	○	●	◑
MAINTENANCE	○		○	◑	○	○	○	○	◑	○
AVAILABLE SPACE	○	○		○	●				●	○
INSTALLATION				◑	◑				●	●
STANDARDS APPROVALS	◑	◑	◑	◑	◑	◑	◑	○	●	◑
DELIVERY / TRANSPORTATION				◑	●	◑	◑		◑	
AESTHETICS					●				●	●
COST	●	●	◑		●	○	○	○	●	◑
OPERATING ENVIRONMENT	●	◑	◑	○	◑	◑	◑	◑	●	○
DOCUMENTATION									●	

● STRONG CORRELATION ◑ MODERATE CORRELATION ○ WEAK CORRELATION

Fig. 7. Correlation matrix [26] for tubular-plate RAPS cells/batteries.

Maintenance-free RAPS batteries

There is little doubt that a valve-regulated, sealed lead/acid (VR-SLA) battery can meet some of the specific requirements of a RAPS system, but certainly not all.

The VR-SLA battery compares favourably with flooded types (either tubular- or flat-plate designs) in terms of self-discharge, charging efficiency, maintenance interval and quality of design and manufacture. There are, however, other significant short-falls in the capability of a VR-SLA battery, namely:

- cyclic discharge reliability
- operating temperature
- cost-effectiveness
- thermal management

Many recent publications have stated that these problems have been resolved. On closer examination, however, these claims may be open to question [27, 28].

The cost-effectiveness is a reflection of both the battery and the maintenance costs. Both flooded and VR-SLA battery systems will require a routine annual inspection and, therefore, the difference in maintenance costs per annum will be minimal. VR-SLA batteries offer only slightly improved specific energy, *e.g.*, a 6 V 150 A h (*C*/10) 'sealed' battery [27] yields 25.7 W h kg^{-1} whereas the equivalent-rated 'Ra-Power' 6Ra160 (Table 1) yields 24.1 W h kg^{-1}. Therefore, because of the increased cost of battery components, the complexity of assembly, and the lower grid and active material utilisation [29] of the VR-SLA designs, the original cost/A h of the two systems cannot be the same and comes down strongly in favour of the flooded designs. Neither gelled-electrolyte nor absorptive-glass-mat types of maintenance-free cells/batteries appear to have fully resolved the 'antimony-free effect' and generally have lower deep-discharge (~80%) cycle lives than those of flooded designs. The best on offer at the moment yields ~1000 [28] cycles (temperature of test not defined); this compares unfavourably with batteries of the 'Ra-Power' range that, to date, have an actual life of 1250 cycles (at 40 °C) and an anticipated life of well in excess of 1500 cycles. The poor performance characteristics of maintenance-free batteries operating at high (tropical environment) temperatures is a further problem that has to be resolved.

Conclusions

By incorporating the latest tubular-plate technology, the 'Ra-Power' range of cells and batteries provides an efficient, reliable and cost-effective energy-storage system for RAPS installations.

A collaborative research project between CBS Batteries Limited and CSIRO will examine, systematically, the phase chemistry and morphological changes that occur during the manufacture of GBO positive-plates, with a view to improving still further the performance, reliability and cost of these plates.

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