Journal of Power Sources, 23 (1988) 233 - 244

DEVELOPMENT OF LEAD/ACID BATTERIES FOR DOMESTIC REMOTE-AREA POWER SUPPLIES

D. A. J. RAND and W. G. A. BALDSING

CSIRO, Institute of Minerals, Energy and Construction, Division of Mineral Products, P.O. Box 124, Port Melbourne, Vic. 3207 (Australia)

Summary

In recent times, there has been a growing recognition of the need for more reliable RAPS systems, both in Australia and in other parts of the world. From the battery point of view, development has, in some instances, been encouraged by a "market push", and in others by a "technology pull". Some manufacturers are seeking to supply customers with batteries that are merely re-labelled motive-power types, others are offering new technologies. In either case, the suitability of the products is unclear because of the poor comprehension of the actual service requirements imposed on batteries in RAPS operations. In order to overcome this deficiency, CSIRO has set in motion a detailed schedule of laboratory and field studies aimed at gaining a greater understanding of battery performance under RAPS duties. It is hoped that the resulting information will lead to specific design criteria for such batteries.

Introduction

Reticulated electricity has been arguably one of the most important contributors to the substantial increase in many peoples' standard of living during the course of this century. However, both in Australia and in neighbouring Asian countries, there are still many individuals, families, and communities who reside in areas that are remote from a mains electricity network. For these people, the costs of grid connection can be prohibitive. To overcome this problem, the concept of the stand-alone power-supply system has been advanced. When intended for operation in remote areas, such a facility is commonly termed a "remote-area power-supply system", *i.e.*, a RAPS system. However, the need for such systems is not determined solely by the tyranny of distance. For example, there can exist a significant number of unconnected properties within an area already serviced by a grid. Extending power lines to these properties may be just as expensive as to those in more geographically remote locations. Given these opportunities, there is wide scope for the development and installation of stand-alone power systems in rural and urban regions of developed countries, as well as in countries with more limited mains electricity networks. Promising applica-

0378-7753/88/$3.50

tions of such systems include supplying power for household, community, telecommunication, street-lighting, navigational, and irrigation services.

Historically, most isolated consumers have relied upon diesel generators to satisfy their domestic electrical power requirements. Diesel/battery hybrid arrangements have also been introduced in order to:

(i) achieve fuel savings (through more efficient utilization of diesel-generator sets);

(ii) extend periods of power availability;

(iii) reduce unwelcome noise levels during sleeping hours.

While the lifetime costs of diesel-based systems have increased, those of more advanced energy technologies, although still high, have begun to fall. For this reason, increasing interest has been shown in the development of RAPS systems that make use of the so-called "renewable" energy sources, *i.e.*, solar and/or wind technologies.

Apart from providing savings in grid-connection and grid-maintenance costs, the development of RAPS systems that incorporate renewable energy sources will also assist the efforts of countries both to conserve fossil fuels for more essential tasks and to protect the environment through absence of unsightly power lines, and reduction in unpleasant noise, vibration, and exhaust emissions associated with diesel-generator operation, etc. However, by virtue of the intermittent nature of such energy sources, a diesel set has usually to be included in most RAPS systems in order to guarantee continuity of power supply. The frequency of the diesel operation will depend upon:

(i) the energy balance of the system, *i.e.*, the difference between the size of the installed photovoltaic (PV) array and/or wind generator, and the size of the consumer load;

(ii) seasonal variations in both the renewable energy inputs and the load requirements.

Rechargeable batteries are normally used to store the electricity derived from the various energy inputs of RAPS systems. The batteries also serve as a back-up facility at night and in times of cloudy or foggy weather (in PV-based systems), or during periods of low wind (in wind-driven generator systems). Although lead/acid batteries are the common choice of energy storage media, their limited performance is the main concern of most suppliers and operators of domestic RAPS systems: in Australia, untroubled service-lives of greater than three years are rarely experienced. Thus, batteries represent not only a large capital investment, but also a significant proportion of the running costs of RAPS systems. Paradoxically, the product of the mature battery industry is short-lived, whilst that of the infant photovoltaic industry is long-lived.

Quite simply, not enough is known at present about the actual power requirements of domestic RAPS systems to be able to design the most suitable long-lasting batteries. For this reason, the CSIRO Division of Mineral Products has conducted an investigation into the typical demands of RAPS systems. A series of battery load–current profiles has been devised for "representative" homesteads (equipped with hybrid PV/diesel-generator/battery power systems) for the laboratory testing of batteries under simulated RAPS operations. These profiles are being used to examine the performance of the different types of lead/acid technology presently being offered by both Australian and overseas manufacturers. Such data provide a valuable benchmark from which to develop purpose-built batteries with better operational characteristics and service life.

Design of RAPS systems

As shown schematically in Fig. 1, a RAPS system can consist of the following components:

(i) primary energy source(s), *e.g.*, PV array and/or wind turbine and/or diesel generator;

(ii) battery bank, to store the derived electrical energy and to maintain supply when climatic conditions are unfavourable;

(iii) control system, to regulate the supply of power to the load and to and from the battery bank;

(iv) power-conditioning system, to convert d.c. electricity from the batteries into a.c. electricity required to operate normal domestic and/or workshop appliances;

(v) load-management system, to reduce peak loads and even out daily demand cycles.

Given the different characteristics of the individual components and the need for reliable, sophisticated, convenient and comprehensive control of the power-supply functions, it can be seen that the design of a cost-effective RAPS system is a complex operation involving a number of engineering, performance, and economic trade-offs.

In terms of simplicity, hybrid PV/battery designs are the ideal choice for remote applications. At present, however, the high capital cost of solar panels precludes the widespread implementation of such hybrid systems as

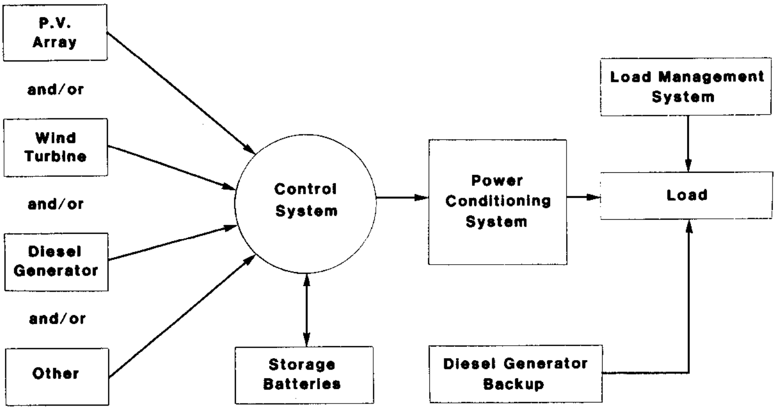

Fig. 1. Components of a typical remote-area power-supply system.

domestic power supplies. As a compromise, the size of both the PV array and the battery capacity are optimized for minimum total-system cost. In addition, a diesel generator is usually included to serve as a back-up power supply during extended periods of inclement weather, to supplement the energy provided by the solar devices during winter months, to accommodate exceptionally high loads, and to prevent excessive discharging and ensure regular full charging of the batteries.

Simulation of battery load–current profiles

Key assumptions

In order to determine the duty requirements of batteries operating in a RAPS system — that is, the battery load–current profile — the following questions must be addressed.

(i) What is the consumer load profile?

(ii) What is the energy source and its input profile?

(iii) What is the system configuration?

(iv) What is the component sizing, *i.e.*, PV-array/wind-turbine size, permissible degree of battery discharge, reserve battery storage requirement, power limits on the diesel, etc.?

(v) What is the control strategy, *i.e.*, simple stop/start switch or complete automatic operation, overload protection, battery bypass facility, battery charging method, temperature compensation, etc.?

(vi) What are the energy losses in the system, *i.e.*, array losses due to clouds, dust, degradation, etc.?

Major difficulties are encountered in attempts to accurately simulate load–current profiles for the laboratory testing of RAPS batteries since:

(i) little detailed information has been gathered on the power inventories of either the renewable energy sources or the consumer loads; at best only annual total and peak-energy consumption figures are available;

(ii) there can be wide variations in the power requirements of consumers in different regions of a given country;

(iii) once power supply becomes available, electricity consumption tends to increase.

Despite the above difficulties, the likely battery requirements of "representative" remote Australian households have been determined in the CSIRO laboratories by using careful estimates of the associated energy-demand and energy-input patterns. The simulation has involved the following key assumptions.

(i) The load represents the domestic requirements of an average-sized family (*i.e.*, 2 adults, 2 children) using normal household appliances and some workshop tools.

(ii) The electrical power is available continuously (*i.e.*, for 24 h) as 240 V, 50 Hz alternating current.

(iii) Renewable energy is obtained from PV arrays only; there is a diesel-generator back-up.

(iv) System sizing is based on current practice and is not explicitly optimized for minimum cost.

Energy demand

Modelling of the consumer load profile is difficult. The most precise method is to record the actual electrical demand at the given RAPS site as a function of time. Naturally, this procedure would require the development and installation of reliable and complex data-logging equipment, as well as considerable consumer education and co-operation. It has been suggested that country-town or city load profiles might be used (there is a reasonable amount of information on those pertaining to Australian situations), but such a proposal must be treated with caution because of some obvious differences in urban and rural lifestyles.

As an alternative to empirical load recording, attempts have been made to develop "prognostic models" of consumer energy-demand profiles. Such models would allow RAPS designers to forecast the energy requirements prior to system installation. While the methodology has still to be fully developed, three key aspects can be readily identified, namely, the need to:

(i) conduct an appliance audit of the household;

(ii) determine the occupants' lifestyle;

(iii) develop a statistical data-base on appliance utilization.

These three aspects are embodied in a load profile of the type shown in Fig. 2. This profile shows the energy demands placed on a small-sized rural PV/battery power-system operating under light domestic loads (2.24 kW h/day).

A survey of published data [1 - 8] on the electricity usage of domestic rural consumers in Australia has shown there to be wide variations between

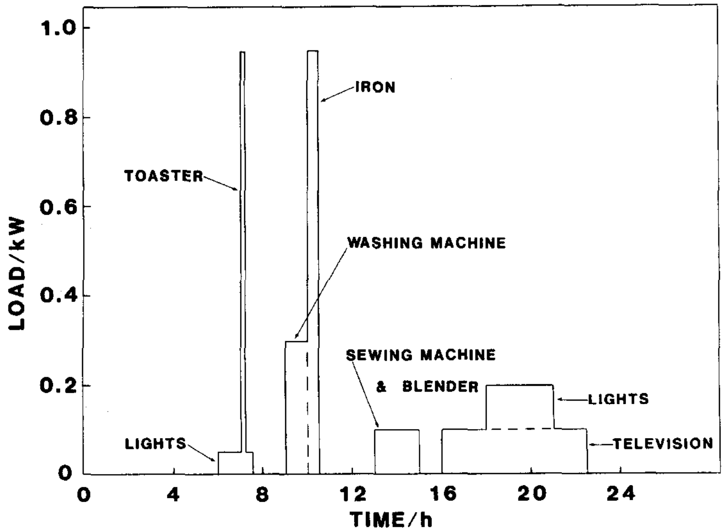

Fig. 2. Energy demands in a small-scale domestic electrical service. Zero time represents midnight.

the annual requirements of consumers in different States, and also between consumers connected to mains grids and those supplied by RAPS systems within a given State. The inter-State variations for grid-connected consumers are primarily due to differences in climate and lifestyle (*e.g.*, the type/number of household/specialist appliances). As highlighted above, it is also clear that once grid supply becomes available, electricity consumption tends to increase. On the other hand, users of small-sized RAPS systems (note, size is subject to economic constraints) generally adapt to the restricted availability and the limited amount of the power at their disposal.

It is important to recognize that refrigeration can account for a significant part of domestic electricity consumption if cooking and water-heating services are excluded. For example, Watt *et al.* [9] have suggested that the combined energy demand of a refrigerator and a freezer (~2000 kW h/year) might be about the same as the total load required by other normal household appliances. The electricity demand will be even higher if a cool room is in use, as is common in remote areas. These findings suggest that there is a strong case for examining the cost benefits of improving the performance of refrigeration units as an alternative to installing larger capacity RAPS systems.

For the purposes of the CSIRO programme, two forms of consumer load profiles have been developed. Figure 3(a) shows the power demand of a representative, remote Australian household utilizing electrical power for lights, a toaster, a food-mixer, a clothes-iron, a washing machine, a sewing-machine/power-drill, and a television receiver (*i.e.*, as in Fig. 2); Fig. 3(b) is the demand for the same conceptual household, but now equipped with refrigeration facilities. In each of these profiles, the annual energy consumption is comparable with that expected for a grid-connected rural household with an equivalent inventory of appliances. Consequently, it is reasonable to assume, at least in aggregate energy consumption terms, that the remote users would suffer only a minimal degradation in lifestyle compared with their grid-connected counterparts.

Energy input

The definitive procedure for determining solar energy inputs to RAPS systems is to record the actual daily insolation at each given site over many years. The use of such information would ensure that the system design would accommodate worst-case insolation levels. Such a programme of measurements is clearly a daunting task, and perhaps not an entirely essential one (see below). To avoid data-monitoring problems, attempts have been made to develop statistical models of insolation input, However, the relative influence of the direct and the diffuse components of the solar radiation at the earth's surface is only partially understood [10], so that accurate time-series models have yet to be developed.

In Australia, monthly average values of the direct and diffuse components (averaged over many years) are available for a number of locations, from which the monthly average, time-of-day, total radiation on a PV array

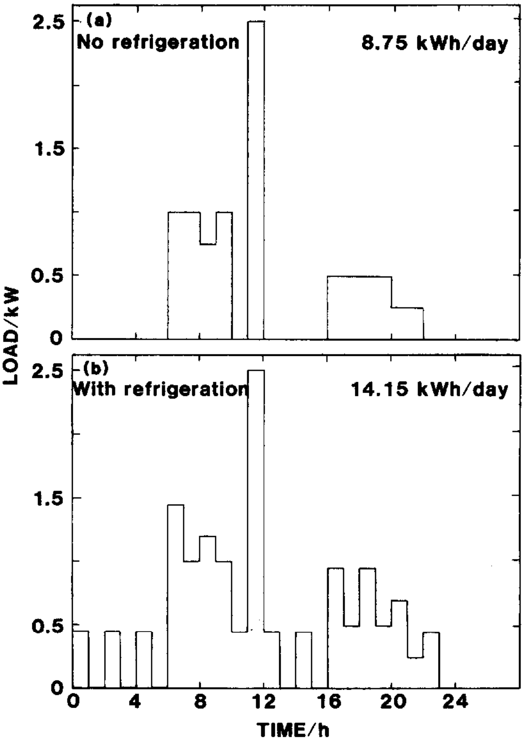

Fig. 3. Load profile for a typical remote household: (a) without refrigeration; (b) with refrigeration. Zero time represents midnight.

can be deduced. However, since it is assumed that all days in the month are identical and equal to the average, and that data for successive years are also the same, this information obviously does not give a true representation of the instantaneous radiation received by a PV array. Nevertheless, monthly average insolation levels could be considered adequate for developing RAPS battery testing profiles for the following two reasons. First, as discussed above, knowledge of the energy demand is severely limited. Thus, the monthly average radiation data are no less accurate than the load profiles, so that seeking more detailed information about radiation inputs would not be justified under the present circumstances. Second, even though radiation levels could experience large changes over short intervals (due to the passage of clouds and other meteorological phenomena), unless such conditions were maintained for extended periods, the effect on the magnitude of the charge stored in the RAPS batteries would be small because the reserve capacity is usually in excess of that required for two or more days' service. The service lives of RAPS batteries would not be affected significantly by such small perturbations in the stored charge.

In the absence of more complete information, and in the interests of simplicity, it has been decided at this stage to adopt a fixed daily insolation profile. The profile, shown in Fig. 4, is representative of the solar radiation

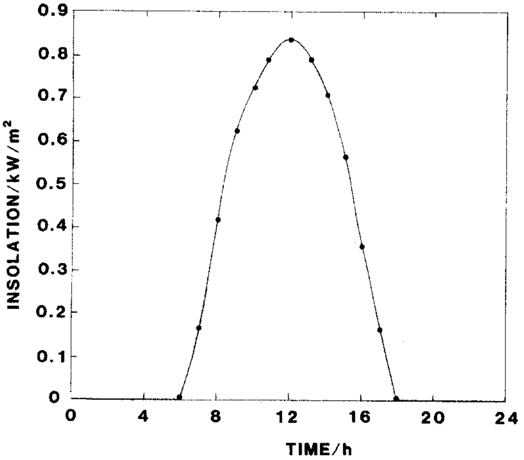

Fig. 4. Insolation profile for RAPS systems. Total incident energy = 6.4 kW h m^{-2}/day. Zero time represents midnight.

input experienced in the western region of the State of New South Wales during a spring or autumn day. For each RAPS system under simulation, the size of the PV array has been chosen so that the derived electrical energy is incapable of meeting the required daily domestic load. The energy deficit is made up periodically by running a diesel generator for a given time. This design strategy has been deliberately selected in order to allow a study to be made of the effect of discharge state on battery life.

Battery load–current profile

The battery load–current profile is the nett difference between the energy-demand and energy-input profiles. On the basis of the information given in Figs. 3 and 4, the following RAPS duty schedules have been simulated:

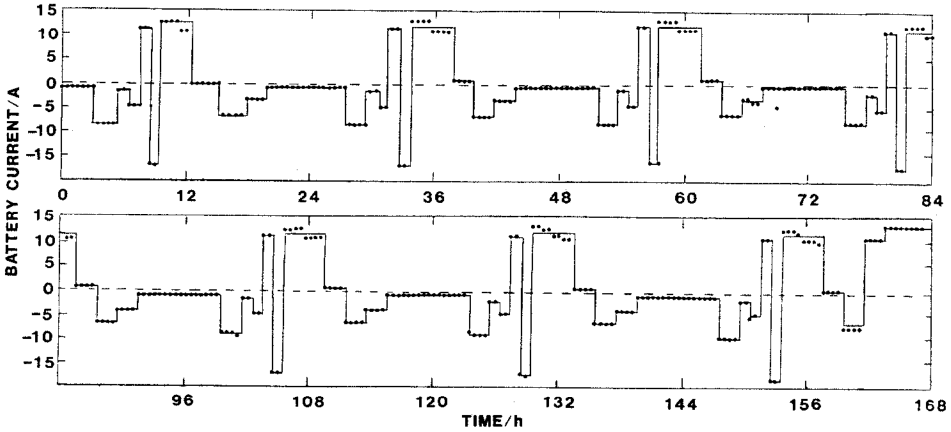

Fig. 5. 7-day duty profile for testing batteries under simulated RAPS service (without refrigeration). Zero time represents 02.30 hours Monday morning.

(i) 7-day profile for household without refrigeration (Fig. 5);
(ii) 3-day profile for household with refrigeration (Fig. 6);
(iii) 1-day profile for household with refrigeration (Fig. 7).

The duration of each schedule refers to the period between successive operations of the diesel generator. In deriving the test conditions, battery charging (during either solar or diesel-generator inputs) is constant-current/constant-voltage controlled, the voltage limit being that recommended by the battery manufacturer.

The purpose of the 7-day profile is to subject batteries to a discharge for an extended period in order to study the possible effects of plate sulphation. Suppliers and users of RAPS systems claim that sulphation is one of the most common modes of battery failure, although it appears that the term is loosely used to cover a multitude of ills. Under the proposed schedule (Fig. 5), the energy from the PV array (*i.e.*, Fig. 4) is insufficient to fully recharge the batteries each day. There is a net daily increase of ~8% in the depth-of-discharge (DOD) of the battery. The DOD reaches a maximum value of ~80% during the morning of the seventh day. Power from a diesel generator then returns the batteries to full charge and the test profile is repeated.

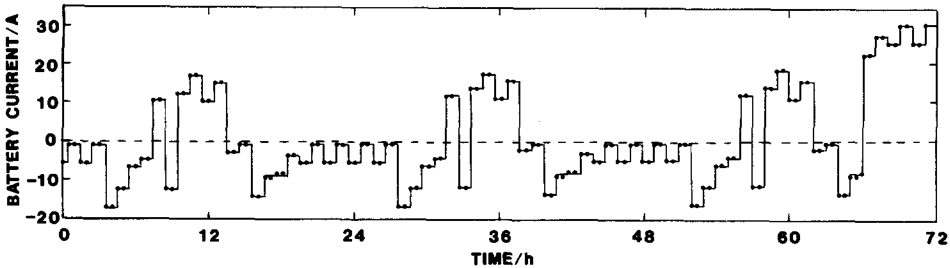

Fig. 6. 3-day duty profile for testing batteries under simulated RAPS service (with refrigeration). Zero time represents 02.30 hours first day.

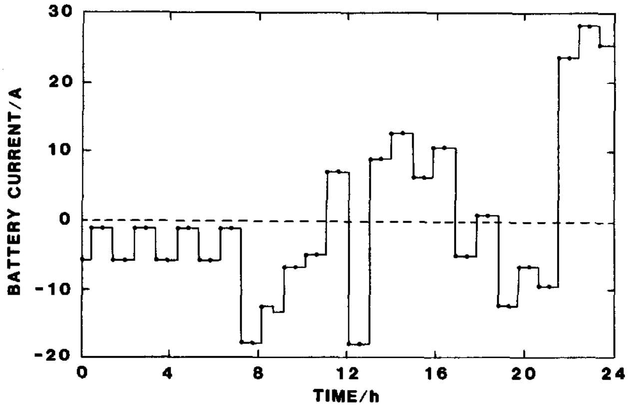

Fig. 7. 1-day profile for testing batteries under simulated RAPS service (with refrigeration). Zero time represents 22.00 hours.

The 3-day profile (Fig. 6) has been constructed in order to examine the effects on battery performance of a household refrigeration load (Fig. 3(b)). A 3-day period of operation (rather than a 7-day period) has been chosen so that the required size (and, hence, cost) of the PV array in the simulated RAPS system is not excessive. Again, there is a shortfall in the energy supplied by the PV array. The battery DOD increases by ~16% each day, and reaches a maximum value of ~60% on the morning of the third day.

In the 1-day profile (Fig. 7), the PV array sizing and diesel operating time are both sufficient to maintain an energy balance in the RAPS system over the test period. Thus, there is no cumulative daily decline in the stored charge of the batteries, as occurs in the 7-day and 3-day schedules discussed above. Under the 1-day profile, batteries are subjected repeatedly to 80% DOD; this test is used for accelerated life-testing of batteries.

Battery testing programme

The battery load–current profiles discussed above are being applied in a detailed laboratory evaluation of the full range of lead/acid technologies currently available on the world market. The aim of these studies is to identify the technology that represents the most effective solution for remote-area power applications. Batteries under test include both conventional flooded-electrolyte designs (*i.e.*, flat-plate and tubular-plate types) and recombinant-electrolyte "maintenance-free" designs (*i.e.*, absorptive-separator and gelled types). The latter technology holds obvious attraction for RAPS systems as it is important for batteries employed in such service to have minimal maintenance requirements and a low rate of energy loss through self-discharge. However, maintenance-free designs generally utilize lead–calcium alloy grids, as opposed to lead–antimony, and this restricts cycle-life under deep-discharge conditions. The problem is collectively termed the 'antimony-free effect', and clearly there would be enormous advantages in finding an alternative alloy component to antimony that provides its benefit of long cycle-life but avoids its electrolyte maintenance problems (arising from the promotion of hydrogen evolution). A parallel research programme is underway in the CSIRO laboratories to overcome the antimony-free effect.

Since it is recognized that service life is not a function of the battery *per se*, but is also dependent upon the architecture, installation, control strategy and maintenance of the total RAPS system, the CSIRO research programme will also involve interactive studies of the performance of the various lead/acid technologies both in a fully instrumented RAPS test-bed and in field service at selected sites equipped with RAPS systems. The *modus operandi* of the programme is outlined in Fig. 8 and involves the following stages:

(i) laboratory testing of batteries under simulated RAPS service to determine the 'best performance' technology (surveying both commercial

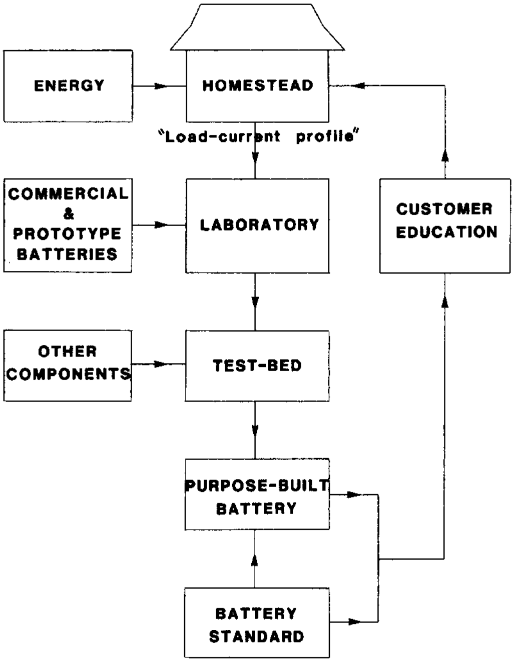

Fig. 8. Progressive stages of CSIRO research programme into development of RAPS batteries.

products and prototype designs developed in conjunction with a local manufacturer);

(ii) placement of technology identified in (i) in a fully-instrumented test-bed to examine the effect of individual, collective, and interactive characteristics of existing commercial RAPS componentry on battery performance;

(iii) using results of (i) and (ii), development of a "purpose-built" RAPS battery well able to meet a performance standard;

(iv) field trials of purpose-built batteries in RAPS systems providing power to domestic loads of commonly encountered sizes, namely, 1, 8 and 20 kW h/day; this stage will be conducted in concert with an education programme to provide users with correct information on procedures for selecting, installing, charging and maintaining lead/acid batteries in RAPS systems;

(v) refinement of laboratory test schedules in accordance with information gathered in (iv).

Acknowledgements

The authors are indebted to the Australian National Energy Research, Development and Demonstration Council for financial support and permission to publish this work; and to R. J. Hill (their colleague) and R. B. Zmood (Royal Melbourne Institute of Technology) for assistance with formulating the battery load–current profiles.

References

1 K. D. Garland, *Proc. Remote Area Power Supply Workshop, 9 - 10 May, 1983, Canberra,* National Energy Research, Development and Demonstration Council, Department of Resources and Energy, Canberra, Australia, 1983, pp. 36 - 52.

2 *Report of the Working Party on Electricity Supply to Remote Areas*, Australian Minerals and Energy Council, December 1984, 64 pp.

3 R. W. Robins and M. J. Williams, *Proc. Remote Area Power Supply Workshop, 9 - 10 May, 1983, Canberra,* National Energy Research, Development and Demonstration Council, Department of Resources and Energy, Canberra, Australia, 1983, pp. 53 - 69.

4 C. N. Watson-Munro, *Proc. Remote Area Power Supply Workshop, 9 - 10 May, 1983, Canberra,* National Energy Research, Development and Demonstration Council, Department of Resources and Energy, Canberra, Australia, 1983, pp. 9 - 18.

5 K. Pendergast, *Proc. Remote Area Power Supply Workshop, 9 - 10 May, 1983, Canberra,* National Energy Research, Development and Demonstration Council, Department of Resources and Energy, Canberra, Australia, 1983, pp. 79 - 85.

6 D. T. O'Flynn and M. Darveniza, An electrical load survey of an individual domestic consumer, *Rep. No. EE 78/6, September, 1978*, Univ. Queensland, Dept. Electrical Engineering, Brisbane, 1978, 36 pp.

7 G. N. Pollard, *Proc. Remote Area Power Supply Workshop, 9 - 10 May, 1983, Canberra,* National Energy Research, Development and Demonstration Council, Department of Resources and Energy, Canberra, Australia, 1983, pp. 70 - 78.

8 T. S. Crawford, *Proc. Remote Area Power Supply Workshop, 9 - 10 May, 1983, Canberra,* National Energy Research, Development and Demonstration Council, Department of Resources and Energy, Canberra, Australia, 1983, pp. 19 - 26.

9 M. Watt, E. Hart and A. Langworthy, *J. Power Sources, 16* (1985) 205 - 232.

10 G. W. Paltridge and C. M. R. Platt, *Radiative Processes in Meteorology and Climatology*, Elsevier, Amsterdam, 1976.