

Predicting the service lifetime of lead/acid batteries in photovoltaic systems

David J. Spiers^{a,1}, Asko D. Rasinkoski^b

^a *Neste Advanced Power Systems UK, PO Box 83, Abingdon, Oxon. OX14 2TB, UK*

^b *NAPS Technology Laboratory, Neste Technology Centre, PO Box 310, FIN-06101, Porvoo, Finland*

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Abstract

In nearly all photovoltaic (PV) systems, solar modules are used to charge a lead/acid battery, which in turn supplies power to the load. Charging and cycling conditions are quite different from those normally encountered in lead/acid battery applications, and prediction of service life needs to take these differences into account. Depending on the nature of the actual application, either cycle life or corrosion resistance (as measured by float-charge lifetime) can be the dominant life-determining quantity. Alternatively, life may be shortened prematurely by an occurrence of a special condition (such as a very deep discharge without rapid recharging). Acid stratification can cause life-shortening effects, and there is evidence that the distribution of stratification is different in PV systems and those applications where a full overcharge is given.

Keywords: Photovoltaics; Lead/acid batteries; Solar; Lifetime; Recovery; Stratification

1. Introduction

Photovoltaic (PV) cells are solid-state devices that convert visible light directly into electricity. Basic physics means that they operate at low voltage (typically less than 0.5 V per cell), so PV cells are series-connected (and environmentally protected) in a larger unit, generally referred to as a PV module (sometimes called a solar panel, but this term is ambiguous). The PV modules themselves may be series/parallel connected to give a PV array of any d.c. voltage and current, as required by the power-supply system.

Below a certain load voltage, a PV module gives a more or less constant current that is proportional to the instantaneous intensity of visible light falling on its surface. In darkness, of course, the module produces no power. Very few practical loads can be run directly from this variable power availability (exceptions are some water pumps, fans, and inverters that feed power into the local grid). In most PV systems, the variable power from the PV module (or modules) is fed into a storage battery and the load takes whatever power

it requires from this battery. The first principle in designing a PV battery-charging system is that the average daily energy production (charging) should slightly exceed the average daily energy consumption (discharging).

Typical examples of PV battery-charging systems are:

- solar-charged consumer products (e.g., portable lamps)
- d.c. systems for lighting, etc., in small houses (often summer and weekend holiday homes) or farms, remote schools, health centres, etc.
- d.c. medical refrigerators in remote health centres (e.g., for storing vaccines)
- industrial remote power supplies, mainly for telecommunications, cathodic protection and navigation lights

In all of the above applications (the list is not comprehensive), a lead/acid battery is nearly always used. Battery selection is often a trade-off between price and the desired performance. Whilst tubular-plate, flooded-electrolyte batteries generally give the best performance in terms of service life, they may not always be affordable to the user. Thus, flat-plate, automotive-type batteries (often modified for PV use) are often used. If flooded-electrolyte, i.e. vented, batteries

¹ Phone: +44-1235-529749, Fax: +44-1235-553450.

are not practical, e.g., in portable equipment or where periodic water additions are not feasible, then valve-regulated batteries are used.

Generally, an electronic charge controller regulates both the overcharge and maximum discharge level of the battery. A simple, series-type, overcharge regulator connects the PV array directly to the battery. This allows whatever charging current is available to pass until a voltage limit is reached: when this limit is reached, it disconnects the array (normally by a relay). A shunt-type regulator also allows available charging current to pass until a voltage limit is reached, but then shunts the current through a solid-state switch. By pulsing this shunt current, the battery can be kept at a more or less constant voltage during the rest of the day. In larger systems, the heat dissipation of a shunt regulator can be a problem, so a multiple set of series controllers is often used to switch segments of the PV array off when different voltage limits are reached. This gives the effect of a finishing charge at lower current and almost constant voltage.

To prevent overdischarge, the charge controller normally operates a relay to disconnect the load from the battery at a voltage that corresponds to a safe maximum depth-of-discharge (normally 80%).

In PV–diesel hybrid systems, the PV array size is often reduced, and any shortfall in its energy production is compensated, from time to time, by a battery-charging diesel generator. In this case, the battery cycles more deeply than in a pure PV system.

2. Factors affecting battery lifetime in PV use

The battery in a PV system experiences conditions that are unlike those in more conventional battery applications. Estimating the service life requires an appreciation of these special conditions, of which the most important are as follows.

(i) Depending on the type of system, the PV duty cycle can fall anywhere between the two extremes of service that are commonly demanded from lead/acid batteries, namely, regular cycling and standby use. A useful measure of this duty is the relative size of the useable battery capacity to the average daily load consumption. This feature is referred to as the number of days of autonomy of the system (i.e., the number of days over which the battery could power the load if there was no charging at all from the PV array because of bad weather or some failure in the system). The higher the number of days of autonomy, the lower the average daily depth-of-discharge, and in the limit of a very large autonomy, the daily cycle is so shallow that the duty cycle approximates to standby use. Some specific examples of this are given below.

(ii) To reduce the water consumption of vented batteries, the voltage limit of the charge-controller is usually set to restrict the amount of gassing at the end of charge. Thus, the overcharge is generally lower than in most other applications, and it is unlikely that the last few percent of fully charged capacity will be achieved. With valve-regulated batteries, the overcharge is similarly restricted to prevent excessive heat production.

(iii) Charging current is variable during the hours of daylight (it depends on the angle of incidence of sunlight on the PV array, i.e., the time of day). Often the maximum charge rate is very low compared with other battery operations.

(iv) The number of Ah available from the PV array for battery charging will vary somewhat from day to day (due to different weather conditions) and from month to month (due to seasonal changes). On a day-to-day basis, the cycle may not be so regular as that calculated from average sunlight availability. On a seasonal basis, the battery may undergo a deeper long cycle of a month or more if the output from the PV array does not match the load demand in the middle of winter.

(v) The discharge rates in PV systems are generally lower than in most other battery uses, typically varying from the $C/20$ rate to the $C/240$ rate, or longer. The available capacity to a particular end voltage is higher than that at the standard rate of $C/10$ or so.

(vi) A deep discharge at a low rate means that the plate active materials are utilized more than is normal. In many PV systems, however, a deep discharge is very rare, and corresponds only to the emergency condition of worst-case bad weather or a charging-system failure. If this does occur, however, recharging could be very slow (several weeks) if it occurs at a time of low sunlight availability, or if there has been a PV-charging system failure at a remote site. The sulphation that must occur under these conditions could be a problem (and there is much anecdotal evidence from the field to support this). To the authors' knowledge, however, there has been no study of the effect of battery type or PV-recharge conditions on whether the effects of this sulphation are permanent.

The depth-of-discharge and its frequency can vary considerably from one type of PV application to another. In order of decreasing overall cycling, the following examples are given.

(i) In some parts of the world, notably Australia, PV systems are used to provide power for remote homes and farmsteads. Mostly, these systems are PV–diesel hybrids, and the batteries are cycled deeply, of the order of 80% every day in extreme cases (a simulated profile of such 'RAPS' use, developed by the CSIRO in Australia is given in Ref. [1]).

(ii) In summer cottages, PV systems are mostly used for lighting, television, etc. only during weekend visits. The battery may be deeply discharged during a visit (up to 80%), but such a deep discharge does not occur every day.

(iii) In small lighting systems (including portable lanterns), the system autonomy is only 2 or 3 days, and the load is always used when there is no charging from the PV array. The average daily depth-of-discharge is then 27–40%, assuming that 80% maximum depth-of-discharge is allowed by the charge controller. Furthermore, lighting is unlikely to be used for exactly the same number of hours every night, and some cycles could be much deeper than this.

(iv) In vaccine refrigeration systems, the specified autonomy is usually 5 days under conditions of heavy use (high ambient temperature and some freezing of icepacks). If the load is considered to be distributed evenly over a 24 h period, only the night-time use (about half of the total daily load) corresponds to battery discharge, and daily cycling is then around 8–10%.

(v) In remote telecommunications systems, customer-specified autonomies of 10–20 days are not uncommon. The load is generally continuous (i.e., a 24 h per day demand) so, again, only about half of it contributes to daily cycling. Under these circumstances, daily cycling is between 2 and 4%.

Cycle life is often proposed as the most important factor in estimating the service life of a PV battery. Given the above range of daily cycles that are possible, however, it should be obvious that this is not always the case. The cycle life of lead/acid batteries is often quoted at only one depth-of-discharge (often 80%). To a first approximation, the cycle life at other depths-of-discharge can be estimated by assuming that the number of cycles multiplied by the depth-of-discharge per cycle is a constant [2]. This is consistent with positive-plate sludging being the limiting factor on cycle life. Thus, for a battery with a stated cycle life of 1100 cycles at 80% depth-of-discharge, its service life at one such cycle per day would be of the order of 3 years. At 40% daily depth-of-discharge, the predicted service life would be 6 years; at 20%, 12 years; at 10%, 24 years; and so on. From experience, it is known that a PV service life of more than 10–12 years in a PV system is rare. Therefore, cycle life alone predicts an unreasonably long battery endurance when the cycling is shallow.

Strictly speaking, a cycle-life correction should be made for the extra capacity that is available at the low discharge rates in PV systems. If, in the example above, the 1100 cycles at 80% depth-of-discharge was given for a battery rated at 300 Ah at the $C/10$ rate, and the cycle test was performed at the $C/10$ rate, then that gives a total delivery of 0.264×10^6 Ah during the

cycle life. If the same battery is rated at 400 Ah at PV rates (say the $C/120$ rate), then the same 0.264×10^6 Ah corresponds to only 825 cycles at 80% of 400 Ah.

In standby use, the daily cycling is zero, and the lifetime is dictated mostly by positive-plate corrosion. Manufacturers of standby batteries will normally quote a float-service lifetime in years at a specific float voltage and ambient temperature (usually 20 or 25 °C). In shallow cycling PV use, service lifetime is likely to be limited by similar plate-corrosion processes, rather than by cycling-induced sludging. As a guideline, it is possible to place an upper limit on the battery lifetime equal to the float service-life. Batteries in remote PV systems, however, are rarely kept in a temperature-controlled environment. Thus, the effect of temperature on the life-limiting corrosion reaction must be taken into account. Manufacturers' estimates of this temperature effect vary slightly, but there is a more or less general agreement that the float life halves for every 8 °C rise in the operating temperature for batteries with lead-calcium or other non-antimonial grid alloys. For batteries with low-antimonial alloys, a halving of the float service-life for every 10 °C rise in temperature is also quoted.

In PV systems where the battery temperature is related to an ambient value that varies from month to month, the ageing effect of temperature on battery performance over the year should be suitably weighted. Using an annual average temperature to estimate this ageing is not informative, due to the non-linear effect of increased temperature on the corrosion rate.

When positive-grid corrosion limits the PV service life, as it can in shallow-cycling PV applications, the operating temperature is very important. Active cooling of the batteries is desirable in a high-temperature PV location [3], if the additional energy consumption can be tolerated. Passive-cooling systems for batteries only increase the heat transfer to the surrounding air and, therefore, will not result in a lower battery temperature than the daily average outside temperature, although they can result in a significant time lag between the two.

Corrosion of the positive plate consumes water. In a vented battery, this water is replaced during normal water additions. In a valve-regulated battery, the water consumed by plate corrosion cannot be replaced, and so corrosion can also lead to accelerated dry-out. An accelerated ageing of valve-regulated batteries under conditions where positive-plate corrosion limits the life might therefore be expected [4].

The factors that determine the lifetime of a lead/acid battery in PV systems can thus be summarized as follows.

Primary factors

- cycle life (corrected for discharge rate) at the appropriate depth-of-discharge, divided by the number of such cycles per year; or

- lifetime on float duty (corrected for operating temperature);
- whichever predicts the shorter life.

In the types of application listed above, it should be obvious that the cycle life will be the dominant factor in deep-cycle duties such as the Australian RAPS systems (80% per day at worst), and the float life will be the dominant factor in very shallow cycle duties like telecommunication systems with 10 days, or more, autonomy. In the intermediate cases, e.g., lighting systems and medical refrigerators, the life-limiting factor can depend on the ambient temperature. At high ambients, the float life (i.e., the plate-corrosion process) is most likely to dominate in these systems.

Modifying effects

- any effects of low overcharge (which at least can reduce the available capacity somewhat, and can also lead to stratification, etc.);
- loss of capacity due to sulphation (e.g., following a deep discharge with slow or delayed recharge)

Catastrophic failure mechanisms, such as manufacturing faults (e.g., weld or feed-through failure), user abuse (use of incorrect acid, poor water quality), are important in determining the actual battery lifetime, but are outside the scope of this discussion.

The effects of the two primary factors, cycle life and float life, are reasonably understandable using conventional battery knowledge (although not often appreciated fully within the PV and battery industries). The main concern over the past few years has been to try to gain a better understanding of the modifying influences on battery life, which are basically due to sulphation and stratification.

3. Experimental

Over the past six years, the authors have carried out tests on various lead/acid batteries under certain sim-

ulated PV-type conditions. These have been mainly aimed at a quick initial evaluation of the suitability of such a battery for use in PV systems. In many cases, these initial tests have been followed by cycle-life testing under PV-type rates and conditions of charge and discharge. This is a very time-consuming process (one cycle per day). The cycle-life testing is not reported here.

The initial tests were aimed at answering two main questions.

- Is the expected capacity delivered under PV-type charging and discharging conditions?
- Can the battery recover from a very deep-discharge at a low discharge rate, followed by a slow recharge under PV-type conditions?

Together with an informed evaluation of the importance of cycle life and float life for the specific PV application, the authors recommend these initial tests to anyone considering the suitability of a battery for PV systems.

Table 1 lists the batteries tested, and their important characteristics. Since it is not appropriate to identify the battery suppliers, in those cases in which the nature of the positive-grid alloy would specifically identify the manufacturer, the alloy is listed only as 'proprietary'. At least two, and preferably at least three, batteries of a specific type were tested under the same conditions at the same time. The results reported are the average of two or three test batteries that gave reasonable agreement.

The types of batteries tested were:

- tubular-plate stationary batteries, as used in most industrial PV applications;
- two types of flat plate, 'low maintenance' batteries specifically recommended by their manufacturers for use in consumer PV systems;
- valve-regulated batteries, all using AGM separators, but with a variety of positive plate alloys; these

Table 1
Batteries tested ^a

Code	Type	Rated C/10 capacity (Ah)	Positive grid alloy	No. batteries tested
TUB1	tubular	150	proprietary (non-Sb)	2
TUB2	tubular	150	Pb-low Sb	2
TUB3	tubular	200	Pb-low Sb	3
FP1	flat plate	85	proprietary (non-Sb)	3
FP2	flat plate	90	Pb-Ca	2
VR1	VR, AGM	192	proprietary	2
VR2	VR, AGM	85	proprietary	3
VR3	VR, AGM	100	Pb-Ca-Sn	3
VR4	VR, AGM	24	Pb-Ca-Sn	3
SVR1	VR, AGM	6	Pb-Ca-Sn	3
SVR2	VR, AGM	7	Pb-Ca-Sn	3
SVR3	VR, AGM	6.5	Pb-Ca-Sn	3

^a VR, AGM = valve-regulated, absorptive glass-mat technology.

batteries are used in some PV systems as substitutes for the above two types of vented battery;

(iv) small valve-regulated AGM batteries (6–7 Ah) of the type that are typically used in consumer products.

Table 2 gives the results obtained from the sequence of tests described below; Table 3 gives the calculated results. An asterisk in the Table signifies that certain tests were not performed for the given battery type. The sequence of tests has evolved throughout the six years of work, so some of the earlier test sequences were incomplete. In other cases, the batteries were being tested for commercial reasons against a tight time schedule, so some of the tests were deliberately omitted. All tests were performed in a temperature-controlled environment of around 25 °C.

The full sequence of tests was as follows.

(i) Precycles/exercise cycles

After a refreshing charge and a $C/10$ capacity check, a few 50% depth-of-discharge cycles were normally given, followed by a further $C/10$ capacity check. If the manufacturer recommended some different precycling regime, this was followed instead.

Table 2
Summary of test results for larger batteries *

Code	Measured before storage			Days storage	Measured after storage		
	C_{10}	C_{100}	PV C_{100}		PV C_{100}	C_{100}	C_{10}
TUB1	124	158	*	22	120	*	127
TUB2	136	179	*	22	150	*	136
TUB3	206	280	279	21	276	280	*
FP1	76.0	90.5	67.3	21	64.0	96.4	74.2
FP2	85.1	*	88.1	21	59.8	*	*
VR1	194	287	249	21	244	256	*
VR2	84.6	95.3	78.0	44	71.8	*	74.5
VR3	106.2	121.7	110.7	39	96.3	*	88.6
VR4	25.6	*	26.5	18	*	*	22.3

* An asterisk means the test was not performed. Days storage = days stored after 100% discharge at $C/100$.

Table 3
Calculated results for larger batteries

Code	Rated $C/10$ capacity (Ah)	Measured before storage			Days storage discharged	Measured after storage		
		C_{10} measured/rated (%)	Measured C_{100}/C_{10} (%)	PV C_{100} PV/normal (%)		PV C_{100} after/before (%)	C_{100} after/before (%)	C_{10} after/before (%)
TUB1	150	83	127		22			102
TUB2	150	91	132		22			100
TUB3	200	103	136	100	21	99	100	
FP1	85	89	119	74	21	95	107	98
FP2	90	95			21	68		
VR1	192	101	148	87	21	98	89	
VR2	85	99	113	82	44	92		88
VR3	100	106	115	91	39	87		83
VR4	24	107			18			87

(ii) C_{10} determination

This was made at a constant current equal to the rated $C/10$ capacity divided by 10 (i.e., $C_{10}/10$), to an end voltage of 1.80 V/cell. It followed a full IU charge with a current limit of $C_{10}/5$ and a voltage limit generally of 2.40 V/cell (although this procedure was different if the manufacturer recommended otherwise, e.g., 2.35 V/cell for most of the larger valve-regulated types).

(iii) C_{100} determination

Following a similar IU type full charge, discharge at $C/100$ to 1.80 V/cell.

(iv) PV C_{100} determination

The battery was charged at $C/50$ until 2.40 V/cell was reached. This simulated a typical charge in a PV system (constant current equal to a typical average charge rate, cut-off equal to that in a typical series regulator). Discharge was as before ($C/100$ to 1.80 V/cell). In some cases, several of these cycles were applied to determine whether the PV capacity stabilized.

(v) Store discharged

The battery was left at open circuit for a period of at least 3 weeks after the last complete $C/100$ discharge. In some of the more urgent tests, the storage time was a little less.

(vi) PV C_{100} after storage

Recharging was done under PV-type recharging conditions ($C/50$ to a specified cut-off voltage). The voltage limit was normally 2.40 V/cell, although in later tests a higher 'boost charge' voltage limit was sometimes used (see below). The subsequent discharge was $C/100$ to 1.80 V/cell.

(vii) C_{100} , C_{10} after storage

In these a full IU recharge was given before the relevant discharge. These tests were a repeat of the initial capacity tests.

The tests conducted on the small valve-regulated batteries were somewhat different, as shown in Table 4. This was because they were being undertaken with a particular product in mind, and the discharge rates

Table 4
Summary of results for small batteries

Code	Measured before storage			Days storage	Measured after storage	
	C_{20}	C_2	C_{20}		PV C_{20}	C_{20}
SVR1	6.77	5.37	6.57	56	5.53	6.13
SVR2	6.90	5.47	6.97	28	6.67	6.60
SVR3	5.67	4.93	5.73	28	5.90	6.23

Table 5
Calculated results for small batteries

Code	Rated $C/10$ (Ah)	C_{20} meas./rated C_{10} (%)	Days storage discharged	After storage (%)	
				C_{20} PV/normal	C_{20} after/before
SVR1	6	113	56	90	93
SVR2	7	99	28	101	95
SVR3	6.5	87	28	95	109

of interest were different. Nevertheless, the philosophy of the 'deep discharge and store' test was the same.

Table 3 collects important ratios of capacities for the larger batteries tested, and Table 5 similar ratios for the small batteries.

4. Results and discussion

4.1. PV capacities and recovery from deep discharge

In most cases, the first measured $C/10$ capacity (after commissioning and exercise cycles) was in accordance with the manufacturers' data sheets. The exceptions were tubular batteries TUB1 and TUB2, which were old samples that had been used previously for other tests, and the two 'maintenance-free' flat-plate batteries FP1 and FP2. The latter were purchased new from their suppliers, but proved to be difficult to charge sufficiently to obtain their rated capacities. Similar effects were noticed with other flat-plate batteries (not reported here) and it seems that the gassing voltage has been made to be as high as possible by various means. This might be desirable in automotive (SLI) use, but is troublesome in PV use.

In general, the increases in measured capacity at the $C/100$ rate compared with the $C/10$ rate were as expected. For the flooded tubular-plate batteries, the increase is of the order of 30%. This is understandable because of the large volume of free acid. Much smaller capacity increases are anticipated for the acid-starved valve-regulated batteries, and a value of around 15% was typical, except for type VR1. Here, an unusually high increase in capacity was observed (48%). The manu-

facturer's data sheet indicates an expected increase of 33%, which is still very high for a valve-regulated battery.

Compared with the nominal $C/10$ capacity, the capacity actually obtained under PV charge/discharge conditions changes due to two different effects, namely: (i) the capacity increase due to a lower discharge rate; (ii) a capacity decrease, due to lower overcharge under PV-type charging. (Effects of temperature are also important in actual use, but are not considered here.)

In many cases, the capacity decrease due to PV-type charging was determined separately. For the low-antimony, tubular-plate TUB3, there was virtually no loss due to PV charging to a 2.40 V/cell cut-off. For the larger valve-regulated batteries (VR1–VR3), there was a much larger loss (9–18%), even though the same voltage cut-off limit was used in the PV-type charge. The charge accepted during the PV charging of these batteries was typically only 101–102% of that discharged in the previous cycle. Under these conditions, the capacity fell from cycle to cycle (see Fig. 1), and was expected to stabilize at a point where this small overcharge corresponds to the overall recharge efficiency. This suggests that a higher PV cut-off voltage is required for the valve-regulated batteries than for the vented tubular batteries, which is contrary to popular opinion in the PV industry. Often, the end user of PV systems with valve-regulated batteries will confuse the PV controller cut-off setting with the battery manufacturer's recommended float voltage or constant voltage charge level, and insist that the PV controller is set to this even lower value. Obviously, the full capacity of the battery is not going to be useable under such conditions. In shallow cycling applications, this effect is probably not noticeable until the autonomy reserve is needed.

Somewhat confusingly, the small valve-regulated batteries tested did not seem to suffer from the same effect of reduced charge efficiency due to PV charging conditions. In part, this might be due to the higher

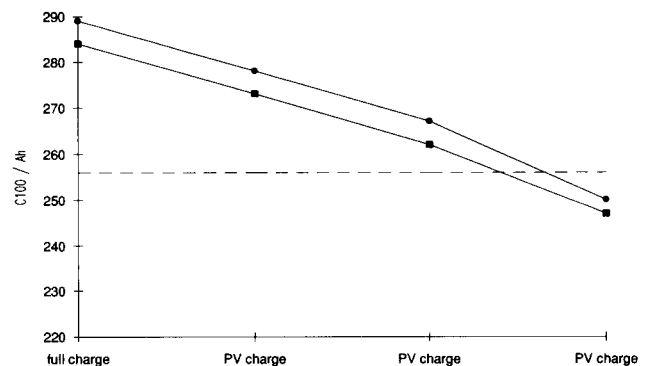


Fig. 1. Falling $C/100$ capacity (2 A to 1.80 V/cell) observed on successive cycles with PV-type recharging (4 A to 2.40 V/cell cut-off) for valve-regulated batteries VR1. Amount of charge accepted is typically 101–102% of capacity delivered on previous cycle. —■—, Battery 1; —●—, battery 2; --- nominal $C/100$.

charging current that is employed in these tests ($C/30$ instead of $C/50$).

The greatest drop in charge efficiency under PV conditions with a 2.40 V/cell cut-off was experienced with the maintenance-free flat-plate batteries. The measured capacity loss for FP1 was 26%. For FP2, a loss of around 15% is estimated if the manufacturer's rated $C/100$ value under full recharge conditions is used. There is no doubt that a cut-off setting for the charge-controller of higher than 2.40 V/cell should be used for such batteries in actual PV systems. Care has to be taken, however, that the d.c. loads that might operate at the same time can tolerate such a high voltage. For example, the voltage of battery FP2 on a constant-current $C/50$ charge rises to 2.66 V/cell at the end of full charging.

Investigation of the recovery after storage in a deeply-discharged condition was the main point of these tests. In many ways, this corresponds to the situation that can happen at some time in the life of a PV system, and it is vital that the battery can recover from such a condition without resorting to special charging methods (not available in real-life PV). For practical testing reasons, the recharging is a little kinder to the battery than in the real PV situation (continuous constant-current, rather than a varying PV current punctuated by night-time absence of charging or even some discharging). An illustration of how these conditions might influence the results is shown in Fig. 2, where alongside the normal continuous $C/50$ recharging, charging was performed with 24 h sequences of: 8 h $C/50$ charge, 16 h open circuit; and 8 h $C/50$ charge, 8 h $C/100$ discharge, 8 h open circuit. These latter sets of conditions correspond more closely to real-life PV conditions, and the last one (partial discharge every day) does indeed result in less capacity recovery for the particular battery

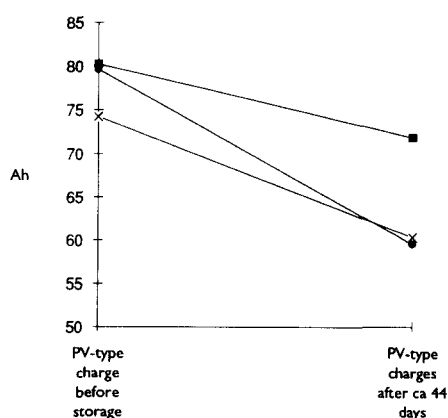


Fig. 2. Different capacity recovery after storage at 100% discharge for VR2 batteries, depending on recharge conditions. Largest capacity loss is when daily charging is followed by partial discharging (i.e., cycling at low state-of-charge). Interrupting the charge current with a daily open-circuit period has considerably less effect on loss of capacity. —■—, 2 A continuous recharge; —×—, 2 A 8 h/0 A 16 h recharge cycle; —●—, 2 A 8 h/—1 A 8 h/0 A 8 h recharge cycle.

illustrated. With the charge controllers used in our PV systems, reconnection of the load after a deep discharge is normally delayed until the battery has been considerably recharged. Also, 100% deep discharge is not obtained in PV systems where the controller restricts the maximum depth-of-discharge (normally to 80%), so it is hoped that this compensates somewhat for the continuous charging in the tests reported here.

The above test does give a relative measure of likely capacity loss in a PV system after a prolonged deep discharge. The results can be seen in the right-hand columns of Tables 2–5. It must be stated that the good recovery characteristics of most of the lead/acid batteries tested came as something of a surprise, given that permanent sulphation is of general concern in PV batteries.

Overall, the tubular-plate batteries recovered excellently from the deep discharge, with little or no permanent capacity loss, as did the small valve-regulated batteries. The larger valve-regulated batteries also recovered but, in most cases, there was a small permanent loss of capacity (at maximum, 13%). Of the flat-plate batteries, FP1 recovered most of its (admittedly low to start with) previously-measured capacity; no more than 5% was lost. FP2 showed the greatest decline in performance (32%), and in this battery there was the most pronounced evidence of sulphation: the voltage during the $C/50$ recharge initially rose quite quickly to about 2.03 V/cell before falling to a minimum of around 1.98 V/cell and, thereafter, it exhibited the normal slow rise. Such a peak in the charge voltage was not noticed with the other batteries tested. Tests on this battery continue, as it is thought that the capacity loss would increase with a longer storage time in the discharged state. The results for the other batteries tested (stored for between 18 and 56 days in a discharged state) suggest that, in this range of times, the effect of storage time on capacity loss is quite small (although it is just about discernable).

There was some evidence that the small battery type SVR3 was still forming (i.e., capacity increasing) during these tests. This was confirmed by subsequent cycle tests with periodic measurements of full capacity. The conclusion, however, is that all three types of small batteries suffered no more than a 10% capacity loss after storage in a deeply discharged condition.

The positive grid alloy probably has an influence on the capacity recovery during this test. Antimony, tin and various other additives are all thought to influence the rechargeability of sulphated batteries. Only in battery FP2, which as far as is known has a grid made of a lead-calcium alloy without any of these additives, is there a problem in recovering most of the 'PV capacity' under the test conditions used here.

Although no impractical tricks were employed to recover the capacity after deep discharge and storage,

an investigation was made of the effect of increasing the voltage cut-off limit for the first PV-type recharge. This use of ‘boost charging’ after a deep discharge can be justified as the logic of the charge controller can be (and has been) modified to increase the charge voltage limit temporarily after a deep discharge has been detected. Fig. 3 shows the capacity recovery for tubular plate batteries (TUB3) with different voltage cut-off limits. This test was subsequently repeated (another deep discharge and storage period) with the batteries swapped around (i.e., battery 1 was given battery 3’s original cut-off, and vice versa, the second time). This confirmed that the recovery only depended on the cut-off voltage and not on the history of the battery.

4.2. Acid stratification

Stratification is generally taken to mean the accumulation of higher density acid towards the bottom of a lead/acid cell under conditions of low overcharge and relatively deep cycling. The different concentrations of acid at different parts of the plates can lead to a local cell action that results in sulphation of the negative plates at the bottom of the cell [5]. There is also a general loss in capacity that is proportional to the extent of stratification [6].

Work in Neste’s laboratories [7] and results reported in Ref. [6] show agreement in the following more detailed stratification behaviour that is relevant to PV type conditions.

(i) During discharge, the fall in acid density at the bottom of the cell (especially in the sludge space) is considerably slower than in the middle and top parts. The resultant density difference is greater for deeper discharges.

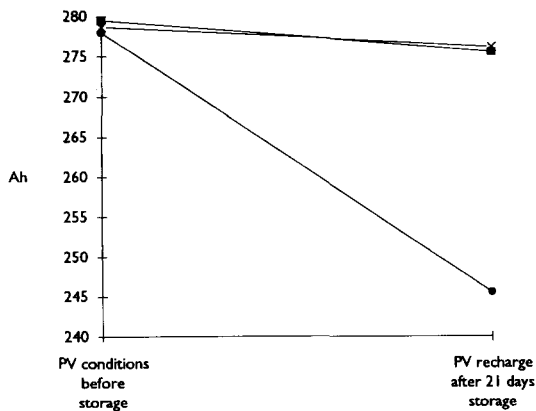


Fig. 3. Different capacity recovery after storage at 100% discharge for TUB3 vented batteries, depending on cut-off voltage of PV-type recharge. Discharge was 2.8 A to 1.83 V/cell. Charging was at 4 A until the cut-off voltage was reached. -x-, 2.58 V/cell; -■-, 2.50 V/cell; -●-, 2.42 V/cell.

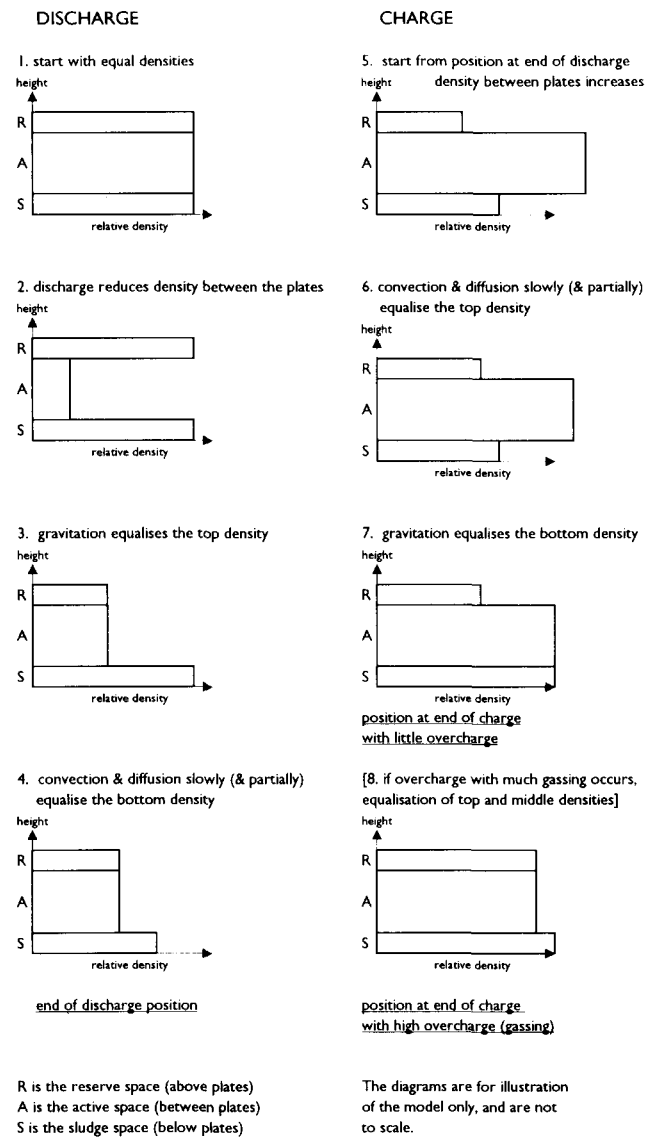


Fig. 4. Simple, stepwise model of acid density changes in vented batteries, leading to stratification behaviour observed under PV-type conditions. A notional first cycle is illustrated: steady-state conditions develop after a few cycles in which stratification is somewhat more accentuated.

(ii) During charging with very low overcharge, the greatest difference in acid density develops between the top of the cell (especially in the reserve volume above the plates) and the middle and bottom parts (which are not too different from each other). This difference in densities between the top acid and the rest depends on the previous depth-of-discharge [6,7], the relative amount of acid above the plates [7], and the charge rate [7] (less stratification at lower rates).

(iii) If significant overcharging is given, then gas evolution mixes the acid between the plates and the reserve volume above the plates. There is not much mixing in of the acid below the plates (sludge space) during gassing. Therefore, the bottom acid density after

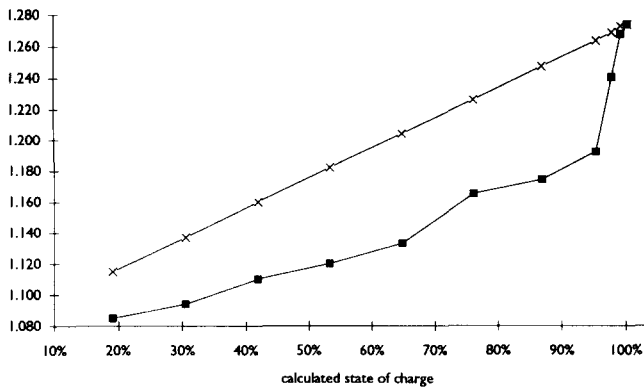


Fig. 5. Differences between observed acid density (■) measurements at top of a flat-plate 125 Ah battery and theoretical acid density (×) calculated from state-of-charge. Recharging was typically 7.5 h at 2 A, followed by 16.5 h at open circuit. Temperature was approximately 23 °C. State-of-charge was calculated assuming a constant 96% Ah efficiency during charge. Top density lags behind calculated value until very end of charging (when gassing occurs), and at least 4% overcharge is needed before the two values agree: —×—, theoretical acid density; —■—, measured top acid density.

overcharge is again somewhat higher than that in the rest of the cell.

A very simple picture of the processes leading to observed stratification effects is given in Fig. 4 (taken from details in Ref. [7]). This considers the acid to be in three separate 'compartments' (above, between and below the plates), ignores actual concentration gradients at different heights within these regions, and considers the different processes that affect the acid density to occur sequentially rather than simultaneously. Despite these gross simplifications, this model has been used to generate numerical equations for the steady-state differences in acid densities that build up under particular cycling regimes after a few cycles, and agreement with observed results is remarkably good [7].

Clearly, from this stratification model, it is necessary to consider not only the build up of higher density acid at the bottom of the cell, but also the development of a less dense layer of acid at the top during charging with the limited overcharge that occurs in PV systems. There is, therefore, also the possibility of some local cell action at the top of the cell on open circuit after PV charging, which might lead to sulphation and capacity loss in PV conditions.

Another, rather practical, consequence of this low acid density at the top of the cell during charging is that a user of PV for lighting, etc., in a holiday home (or other building without grid electricity) can get a false impression of the battery's state-of-charge if a

simple density measurement is made with a hydrometer. Fig. 5 illustrates the differences between the measured top acid density and the theoretical acid density based on the amount of Ah or recharge given. This test was done on a flat-plate battery (not one of those reported earlier as FP1 or FP2) under PV-type conditions (including simulated overnight absences of charging). The user of the PV system may conclude that there is something wrong, and might take unnecessary actions as a consequence (like bypassing the charge controller, or even adding acid to the battery).

Whilst the modifying effects of stratification on PV battery life are not known at present with any certainty, the phenomenon of 'top stratification' must be considered alongwith the more usually-recognized 'bottom stratification' effect. Notice should also be taken of the fact that the top acid during PV charging will not have a representative density, and users must be made aware of this so that dissatisfaction does not occur, and potentially damaging measures are not taken.

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