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Characteristics of a high-performance lead/acid battery for electric vehicles — an ALABC view

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Abstract

As the electric automobile at last becomes available to customers of the major automobile manufacturers, the debate over what are the essential performance characteristics that will encourage large-scale electric vehicle (EV) penetration of the domestic transport sector continues unresolved. All are agreed that the EV battery is a key element in this consideration and, accordingly, the development of candidate batteries is currently proceeding at an unprecedented rate. This paper considers the several parameters that will influence strongly the purchase decision for EVs and proposes a simple methodology for rating the performance of candidate batteries against a single benchmark. The progressive development of the valve-regulated lead/acid (VRLA) battery through the 1990s to meet the required performance is then reviewed. © 1997 Published by Elsevier Science S.A.

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1. Introduction

The use of battery-powered electric rather than internal-combustion engined (ICE) vehicles has been an option since the turn of the century. Enthusiasm for electric vehicles (EVs) was high initially, before ICE vehicles were developed, and rose again during the world oil crises of 1973 and the early 1980s. Through the 1990s, however, the incentive for the introduction of EVs has changed to a need to improve air quality in the large centres of population in California and in the northeastern states of the USA, as well as in other countries in Europe and South-East Asia. The prospects for large-scale introduction of EVs over the next few years are at an all-time high, particularly since the need to replace oil-based fuels will return as an additional issue progressively during the early years of the next century.

There is a widespread view that, when ICE vehicles and EVs are manufactured on a similar scale, EVs will attract a lower cost since they incorporate far fewer moving parts.

The progress of the EV market, from its present stage to the point where the economies-of-scale take effect, will be influenced by the characteristics of the vehicle. These, in turn, are effectively dictated by the performance of the vehicle's battery.

The Advanced Lead–Acid Battery Consortium (ALABC), which comprises 48 members from the lead production, battery and component manufacturing and related industries, was founded in 1992 in order to meet the challenge for improved EV batteries. The pooled resources of the Consortium membership have enabled a worldwide research and development effort to advance the performance of lead/acid batteries for EVs to a remarkable degree during the four years since the Consortium's work began. This paper reviews the battery performance characteristics that are necessary for EVs to be marketed successfully and monitors the progressive development of the valve-regulated lead/acid (VRLA) battery through the 1990s to meet this required performance.

2. What is an acceptable performance for an EV battery?

The list of virtues that an EV battery should exhibit ought to include at least the following:

1. low purchase price
2. high performance (power)
3. recharge convenience (adequate range per charge, short recharge time)

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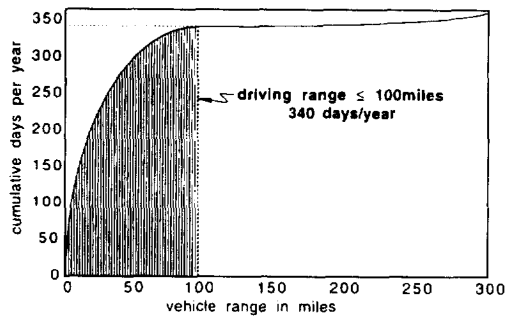

Fig. 1. Typical daily travel characteristics for North American vehicles. Statistics of the US Department of Transportation.

4. low running cost (long life, no maintenance)
5. materials recycleability
6. safety
7. efficiency
8. low self-discharge
9. low environmental impact
10. resistance to abuse.

The EV is attractive as a clean and quiet mode of transport and, for the first years, there will undoubtedly be some novelty appeal. Increasingly, however, it will be necessary for the EV to measure up against the performance of its ICE equivalent.

The lead/acid battery already has a specific power that will offer acceleration that compares very favourably in traffic [1]. Therefore, the acceptability debate centres on recharge convenience and running cost. US Department of Transportation statistics [2] indicate that the typical daily range of personal driving is less than 50 miles for 75% of the time, and less than 100 miles for 93% of the time (Fig. 1). In Europe, journey lengths are even shorter with most trips no longer than 50 km [3]. In order to achieve a range of 100 miles per charge, it is probably necessary to provide a battery with a specific energy of close to 50 Wh kg^{-1}. Although 100 miles is a relatively short range compared with what is achievable in today's ICE automobiles, this possible limitation of EVs could be largely offset if the battery could be recharged quickly.

A long cycle life is necessary in order to amortize the cost of the battery over as long a time as possible.

A recent study of the household market for EVs in California [4] provides strong evidence of a market large enough to fulfil the sales that were to have been mandated for 1998 and 2001 by the California Air Resources Board, i.e., approximately 20 000 and 50 000 vehicles, respectively. Moreover, this market can be satisfied with currently available technology.

The ALABC technical program that began in 1992 set out to build on the VRLA battery's established strengths of low purchase price, high efficiency, established safety, very low self-discharge, high economic recycleability, etc. In order for the technology to gain substantial market-place acceptance, five critical goals were set, see Table 1.

3. A convenient method for evaluating the status of candidate EV batteries

As battery technology advances in response to the needs of the EV market, it is desirable to be able to benchmark progress. There might be a temptation to focus solely on driving range per charge in order to obtain a comparison in terms of a single parameter, e.g., 'batteries offering large values of specific energy are better than those offering small values of specific energy'. Such an approach would be naive, however, since cost and life (at least) are also clearly central parameters in the purchase/no-purchase decision. A battery with an enormous specific energy and a very short life will not succeed in the market place, nor will a battery with a very large cost.

An approach that allows single-figure evaluation of different batteries, without failing to take account of vital parameters, is through the use of a synthesized 'figure-of-merit' (FOM). This combines the several parameter values that exercise a vital influence on the acceptability of a battery into a single expression, the value of which can be used to compare different batteries. An example of such a FOM would be

$$\mathrm{FOM} = \frac{\text{specific energy } (\mathrm{Wh\,kg^{-1}}) \times \text{life (cycles)}}{\text{cost (US\$ per kWh)}} \quad (1)$$

The value of the FOM would be increased by increasing specific energy and/or life, or by decreasing cost. Clearly: the higher the FOM, the better the battery. The FOM is the simplest expression possible, but it is arbitrary in form and the numerical value has no direct significance.

An alternative and far more useful approach is to use the same three parameters to calculate the fuelling cost of the EV. This can be done as follows. Assume, for example:

1. number of miles per charge = 2 × numerical value of specific energy (e.g., 50 Wh kg^{-1} = 100 miles)

Table 1
ALABC performance goals

Purchase cost	Specific power	Specific energy range	Recharge time	Cycle life [a]
US$ 150/kWh	150 W kg^{-1} at 80% DOD	50 Wh kg^{-1} at 3 h rate	50% at 5 min 80% at 15 min 100% at 4 h	500 (with less than 20% loss of capacity)

[a] Simplified Federal Urban Driving System (SFUDS) cycles.

2. EV has a 16 kWh battery
3. battery is discharged to 80% (depth-of-discharge (DOD)) each cycle
4. coulombic efficiency is 80%
5. electricity cost is, US$ 0.10 per kWh.

Then:

cost of electricity

$$= \frac{\text{battery energy} \times \text{DOD} \times \text{price/kWh} \times \text{efficiency}}{2 \times \text{specific energy} \times \text{DOD}} \quad (2)$$

battery depreciation cost

$$= \frac{\text{battery capacity} \times \text{battery cost per kWh}}{2 \times \text{specific energy} \times \text{cycle life} \times \text{DOD}} \quad (3)$$

total fuelling cost (per mile)

$$= \text{cost of electricity} + \text{battery depreciation cost} \quad (4)$$

Thus, the FOM in this case (i.e., the total fuelling cost) is a useful number, the significance of which needs no explanation and is equally applicable to any type of battery. For the ALABC target parameters (Table 1), the cost of ownership turns out to be US$ 0.07/mile.

This latter FOM provides a ready means of assessing the effectiveness of changes that are made to the battery as the technology advances. It also enables a ready comparison of the utility of different types of battery (chemistry) and allows a comparison with the running cost of an ICE vehicle.

4. Progress of VRLA technology for EVs through the 1990s

The development of the key parameters for an advanced VRLA battery for EVs between 1992 and 1995 are indicated in Table 2, together with a prediction for the values of the parameters for 1998. It is clear that, in 1992, the VRLA was a poor candidate for powering EVs. The modest specific energy and poor cycle life translated to a cost of ownership in excess of US$ 1.00/mile. Further, the recharge time for a lead/acid battery at that time was set at around 8 h so that a daily range of 50 miles could not be exceeded.

Between 1992 and 1995, intensive programs of development of VRLA batteries yielded significant progress. By the end of 1995, VRLA batteries offered for EVs by a number of manufacturers showed specific energy reaching 35 Wh kg^{-1}, a cycle life of around 500, and a cost reduced to US$ 150/kWh. Taken together, these characteristics translate into a cost of ownership that has been reduced by an order of magnitude over a period of three years. In addition, the ALABC has carried out a substantial program for developing the possibility for fast charging lead/acid batteries [5] and, in an extensive evaluation of some 30 different types of lead/acid batteries at Cominco, it was found that all were able to return 50 and 80% of their charge within 5 and 15 min, respectively, without suffering any apparent damage. Indeed, some of the VRLA battery types cycled through a rapid recharge regime extremely well for many cycles. This work not only demonstrated that it was possible to recharge available lead/acid batteries conveniently, but it also indicated that fast charging may be beneficial.

A further ALABC program at Cominco has set out to investigate the origins of the apparent improvements that can be achieved during fast charging. In this program, a set of batteries is being charged, some at high rates and some at low rates, and it is the intention at the end of the test to conduct a tear-down analysis in order to identify possible differences between the microstructures of the active materials in the two cases. As shown in Table 3, however, this

Table 3
Effect of fast charging on charge efficiency and cycle life

	Charge efficiency (%)	Cycles
Low-rate charging [a]	87	250
High-rate charging [b]	97	960+

[a] The low-rate charging was carried out according to a constant-voltage regime to be completed in 10 h and was followed by a $C_2/2$ discharge to 80% DOD.
[b] The high-rate charging regime restored 80% of charge in 15 min and after each five such cycles a 4 h charge was applied. The discharge regime was the same as for the low-rate test.

Table 2
Development of parameters for advanced VRLA batteries for EVs

	Specific energy	Range	Cycle life [a] (cycles)	Recharge time	Purchase cost (US$/kWh)	Cost of ownership (US$/mile) [b]
1992	25 Wh/kg	50 miles	75	100% at 8 h	200	1.09
1995	35 Wh/kg	75 miles	500	50% at 5 min 80% at 15 min 100% at 4 h	150	0.10
1998	48 Wh/kg	100 miles	800	50% at 3 min 80% at 10 min 100% at 30 min	100	0.04

[a] SFUDS cycles.
[b] Includes energy at US$ 0.10/kWh.

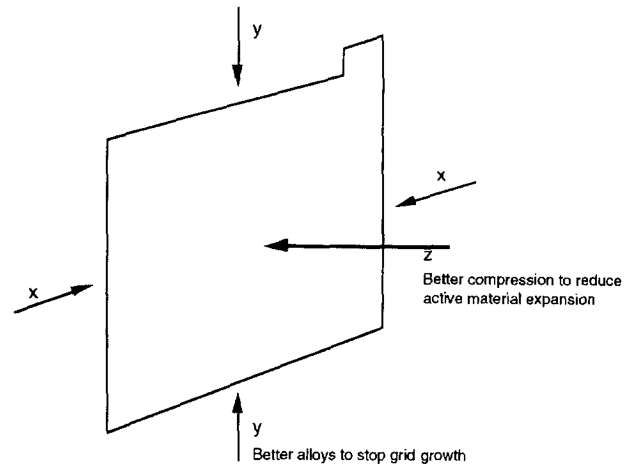

Fig. 2. The life of a lead/acid battery plate may be curtailed by the tendency of the microstructure of the active material to evolve with cycling. The tendency is for the active mass to occupy a progressively larger volume and for its inter-particle connections to be lost unless this process is prevented. The life of the battery can be preserved by resisting the tendency to grow: (i) in the plane of the plate (x- and y-directions) by employing grid alloys that have high creep resistance, and (ii) in the direction normal to the plate (the z-direction) by the application of pressure to the plate stack.

program has already revealed some dramatic differences in performance. The charge efficiency and the cycle life for the high-rate case have far exceeded the equivalent performance of the batteries being charged at low rates. This result confirms earlier work at CSIRO [6] that first showed how fast charging benefits cycle life.

All of these results, obtained as they are in laboratories, are encouraging but it is necessary to confirm that they are reproducible in on-road EVs. In a program run by the Arizona Public Service Company (also an ALABC member), there has been a dramatic demonstration of what is possible with fast charging. Several EVs have been used every day in real road driving duty on the streets of Phoenix (AZ) and, once a month, evaluated for range on a test track. These vehicles have been treated extremely roughly and yet have delivered over 14000 miles of duty with in excess of 200 fast charges. These charges enable the EVs to achieve daily ranges of well over 100 miles. It is impossible to over-emphasize the importance of this work since it shows that the lead/acid battery can meet the demands of EVs and can provide the level of convenience that the user requires over a sustained period of time [7].

Much of the technical progress made by ALABC programs around the world has yet to reach full implementation within commercial product and it is anticipated that by the year 1998 the specific energy and the life of VRLA batteries will have advanced still further. The 1995 specific energy value (Table 2) is achieved with grid thicknesses of around 2 mm and a positive active-material utilization of around 30% at the 1 h rate. Within the ALABC development program, a change in grid-alloy composition is providing a sharp improvement in both strength and corrosion resistance [8] that allows grid weights to be reduced by a factor of at least 2. In addition, additives employed by CSIRO in the positive active-mass have raised the utilization at the 1 h rate to over 40%. These two advances are estimated to raise the specific energy, even for conventional designs of VRLA battery, close to the target value of 50 Wh kg^{-1}. Advanced designs of lead/acid battery (bipolar, quasi bipolar [9]) may perform even better.

The cycle-life target for the VRLA battery will be to achieve the same performance as the flooded system from which it was developed (over 1000 cycles). There is a growing appreciation of the need to render the grid alloy resistant to creep, to maintain the plate within a firm compression regime (Fig. 2) [10] and to control the details of the recharging algorithm. Efforts in these three areas are already proving to be very successful.

Over the same period, i.e., to 1998, the cost of the battery is likely to have reduced to somewhere near US$ 100/kWh and the derived refuelling cost for an EV based on such lead/acid batteries will be some US$ 0.04/mile (Table 2). Thus, cost will be comparable with what is possible with an ICE vehicle. A specific comparison of the state-of-the-art is given below.

5. Comparison with ownership costs of ICE vehicles

A recent study carried out by Electric Transportation Applications [11] compares the cost of ownership of a battery-powered EV and an ICE vehicle. Ownership costs were considered to include electricity plus battery amortization in the EV case set against fuel plus oil for the ICE, with maintenance and tyre costs added separately to each case. Fuel costs were taken from values that were current as of June 1996, although it was acknowledged that these will rise in the future. Historical trends were taken to indicate that costs for maintenance and tyres were stable and predictable. Tyre costs for the EV were expected to increase by up to a factor of 2 in comparison with the ICE vehicle, but maintenance costs were expected to be very much less. The analysis was carried out for a Chevrolet S-10 pickup and the comparison data (Table 4) indicate

Table 4
Variable cost comparison (in US$/mile) for ICE-fueled and battery-powered variants of a Chevrolet S-10 pickup [a] [9]

Item	Gasoline (US$/mile)	EV (US$/mile)
Fuel and oil (electricity in the EV case)	0.0839	0.0063
Battery amortization		0.117
Maintenance	0.0339	0.0085
Tyres	0.0141	0.0282
Total	0.1319	0.16

[a] Cost figures are for 1996. The EV is assumed to have VRLA batteries with a 20000-mile warranty and a replacement cost of US$ 3500.

that, in 1996, ownership costs favoured the ICE vehicle by about US$ 0.03/mile. It is clear that the ICE is most sensitive to the price of fuel, while the EV is most sensitive to the battery amortization cost. Thus, as fuel prices rise and battery costs fall (life increases, etc.), future trends are for the comparative cost to progressively move in favour of the EV, as anticipated in Table 2.

6. Conclusions

Many of the attributes of a candidate battery influence its suitability for use in EVs but purchase price, specific energy (range per charge) and cycle life impact directly on the ownership costs. Calculation of ownership costs provides a ready means of monitoring relevant progress of a particular battery type, of comparison between battery types (chemistries), and of comparison with the equivalent ICE vehicle. The performance of the VRLA battery has advanced markedly in recent years to the point where ownership costs of an EV have fallen close to those for an ICE vehicle. Within the next few years, the ownership cost comparison is likely to favour the EV.

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