ELSEVIER

Journal of Power Sources 84 (1999) 237–242

JOURNAL OF POWER SOURCES

www.elsevier.com/locate/jpowsour

High-rate, valve-regulated lead–acid batteries — suitable for hybrid electric vehicles? [1]

Patrick T. Moseley *

Advanced Lead–Acid Battery Consortium, P.O. Box 12036, Research Triangle Park, NC 27709-2036, USA

Accepted 28 June 1999

Abstract

The possibility of replacing, with electric drive systems, at least some of the internal-combustion engines currently employed in road vehicles is being actively pursued by all the world's major automobile manufacturing companies. Minimum on-road emissions would be achieved by the adoption of pure electric vehicles, but the somewhat limited range available between charges of the batteries has led to a serious evaluation of hybrid electric vehicles as an acceptable compromise. In hybrids, a small internal-combustion engine, operated at high efficiency, will consume less fuel and produce less emissions than would a regular internal-combustion engine, and will allow considerable range extension over the pure electric vehicle. Eventually, an electric system which employs a fuel cell may become affordable. It is likely that all three systems — the pure electric, the hybrid electric, and the fuel cell system — will require battery support, particularly to provide boost power for acceleration and hill climbing. Although more expensive battery systems are being vigorously developed in pursuit of greater range per charge, the benchmark against which these systems are compared remains the valve-regulated lead–acid (VRLA) battery.

Keywords: Lead–acid batteries; Electric drive systems; Hybrid electric vehicles

1. Introduction

As the turn of the millennium approaches, we are witnessing the first stages of perhaps the greatest change in the technology of road transport that has taken place for a hundred years.

All the major automobile manufacturers are moving in anticipation of increasing pressure to reduce the dependence on oil for road transport. This is because there is increasing alarm over atmospheric pollution since ozone levels are above minimum hazard concentrations in many of the major conurbations of the world. In addition, it is seen to be strategically unsound to rely upon a raw material which is in finite supply and even now is primarily available only in some privileged regions of the world. Finally, there appears to be concern felt by many about the possible harmful effects of continued massive release of carbon dioxide into the global atmosphere.

Although the optimum route to a resolution of these problems is not entirely clear, there is a broad consensus that it will involve the replacement of the internal-combustion engine by an electric drive-train and the reduction, if not the elimination, of oil products as the primary fuel for motive power.

The obvious first step towards ameliorating the twin transport problems of pollution abatement and oil conservation would be the development of the pure electric automobile, a concept which has been investigated on and off over a considerable period. Unfortunately, past attempts to introduce electric road vehicles largely failed because the technology was not adequate and/or the need was not pressing.

Since the beginning of the 1990s, however, there has been insistence from the Air Resources Board in California, and elsewhere in the world, that the need for electric vehicles *is* now sufficiently pressing. Meanwhile, the pioneering work of the major automobile manufacturers has shown that the technology — at least in terms of vehicle design — *is* now adequate. The challenge to replace the thoroughly established automobile with a vehicle which

* Fax: +1-919-361-1957; E-mail: pmoseley@ilzro.org

[1] The performance of VRLA batteries intended for use in electric vehicles has advanced remarkably during the present decade, especially with respect to their high-rate (power) capability. This paper discusses the suitability and prospects of VRLA batteries for hybrid electric vehicles.

0378-7753/99/$ - see front matter
PII: S0378-7753(99)00323-7

has entirely different characteristics, and is starting from scratch, is great indeed. For example:

- How to reach economies-of-scale when the first items off the production line are far more expensive than the familiar internal-combustion engine equivalent?
- How to cope with anxiety over range limitation and, possibly, the long refuelling time conventionally associated with replenishing the stored energy supply?

There are a number of options. For a pure electric vehicle, a choice can be made between an expensive battery which provides a moderate range per charge, or an affordable battery with a modest range per charge — albeit this charge can be replaced in a few minutes.

The hybrid electric vehicle offers an alternative approach. In this design, the motive power is provided by an electric motor which is fed by a battery, and is supplemented by a small internal-combustion engine. With such an arrangement, the engine can be managed far more efficiently than in a conventional vehicle with the result that fuel consumption and exhaust emissions are both reduced.

Moreover, the use of a fuel cell as the primary power source will further reduce fuel consumption and exhaust emissions.

The lead–acid battery is the starting point for the battery component in all of these options because:

- it is already manufactured in an established industry sector;
- it is likely to be the lowest cost option for many years to come;
- it is a thoroughly recycled product.

The present paper examines how the current VRLA battery shapes up to the demands of the electric vehicle and, in particular, the hybrid electric vehicle.

2. Batteries for electric vehicles — essential attributes

A recent EPRI survey [1] expressed the view that there will be a market ‘‘in the next several years’’ for electric vehicles with a driving range of between 100 and 120 miles (160 and 190 km) that should be 1.5 to 2% of the total vehicle sales in the United States as a whole and 3 to 5% in California alone. A survey of the daily journeys of drivers in North America has revealed that a range of 80 miles (130 km) will satisfy the needs of 90% of these drivers and that there is a long tail for the remaining 10% of drivers that extends into well over 150 miles (240 km), and probably to 300 to 400 miles (48 to 640 km) Fig. 1.

In order to achieve a successful introduction, the electric vehicle must satisfy customer expectations in all respects. In particular, it is becoming increasingly clear that the vehicle must match the internal-combustion engine equivalent in terms of acceleration, but at no additional cost. It is inevitable that the driving range between battery recharges for an electric will be less than the driving range between refills of the fuel tank of the internal-combustion engine vehicle. This restriction, provided it is not too severe, can be offset to some extent by the convenience of being able to recharge at home rather than having to visit a gas station. The data in Fig. 1 indicate that a viable electric vehicle should have a range of at least 100 miles (160 km) between charges. If the driver wishes to cover a greater number of miles than is achievable in one charge, then the key characteristics will be the ability to recharge the vehicle both rapidly and in a manner which should resemble as closely as possible the refilling of the fuel tank.

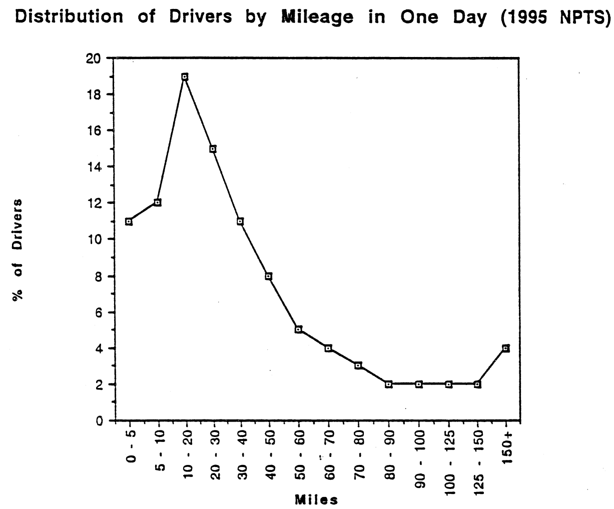

Fig. 1. Daily driving range for drivers in North America.

Battery consortia broadly agree that the crucial parameters for the battery are cost, specific energy, specific power, cycle life, and the ability to take a rapid charge. The dilemma for vehicle manufacturers is that, on the one hand, the lead–acid battery meets most of the targets but is only just reaching the lower limit of acceptable range performance while, on the other hand, alternative batteries meet a different subset of the targets and appear unlikely to be able to reach an acceptable cost, at least not for some considerable time.

3. Recent advances in valve-regulated lead–acid batteries

Although the traditional flooded lead–acid battery has a long history, it was clear to all concerned at the beginning of the present push for electric vehicles (and hybrids) that a sealed (‘maintenance-free’) product would be essential. Accordingly, the valve-regulated lead–acid battery was adopted. The history of this product is scarcely longer than some of the alternative battery chemistries.

At the beginning of the 1990s, the available valve-regulated lead–acid batteries had a very poor cycle life under duties encountered in EV operations coupled with a modest specific energy and a long time for recharge (Table 1). Fortunately, during the world-wide programme of research and development carried out by the Advanced Lead–Acid Battery Consortium (ALABC) through the 1990s, the performance of valve-regulated lead–acid batteries designed for electric vehicles has improved dramatically.

3.1. Specific energy

In the ALABC's technical programme the limitation of low specific energy (equates to short driving range) has been tackled head-on. Substantial projects have been put in place to develop high specific energy by novel approaches to weight reduction. These are being carried out in the factories of major battery manufacturing companies. In one such project, the use of very thin flat plates, around 20% of the thickness of conventional technology, offers substantial weight savings [2]. In another approach, very thin tubular designs are being explored with plates prepared by stamping from thin foil which is rendered rigid and heat resistant by a rolling process [3]. In both instances, the technologies are being developed in a range of variants in order to optimize the technology. Both battery designs are making use of novel, corrosion-resistant alloy formulations which have been identified by ALABC's contractors in France [4]. Ultimately, it is likely that these initiatives will result in specific energies which approach twice the levels achieved in 1990.

3.2. Cycle life

The causes of early limitations on life (Table 1) have been studied thoroughly and addressed directly. It has been shown [5,6] that valve-regulated lead–acid batteries can achieve substantial improvements in life through the application of proper and sustainable compression. The alloys identified during the ALABC programmes in France [4] display not only improved corrosion resistance but also high creep strength which also helps to retain the active material within the necessary restricted volume to allow long life [7].

Several research studies (e.g., Refs. [8,9]) have shown that it is absolutely essential to charge the valve-regulated lead–acid battery correctly in order to achieve long life.

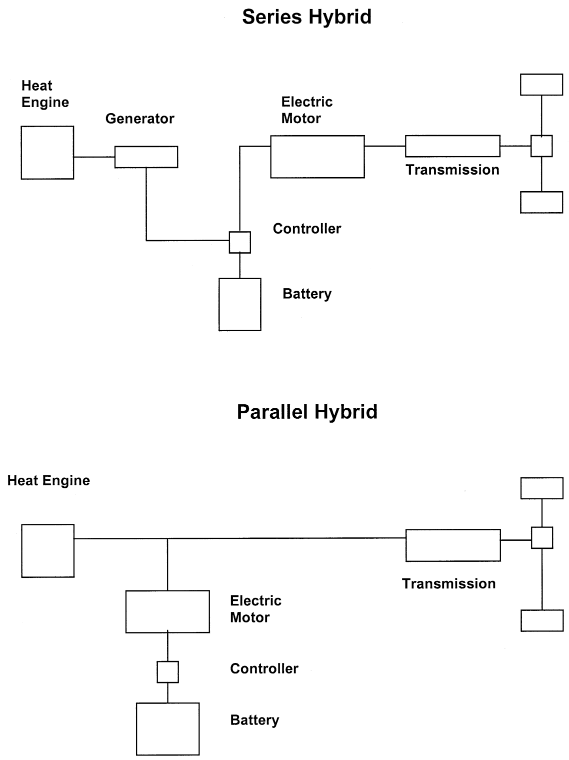

Fig. 2. Schematic representation of series and parallel hybrid electric vehicles.

3.3. Recharge time

Response to recharge regimes provides the clearest demonstration of the difference in operating behaviour of valve-regulated and flooded lead–acid batteries. An initial study [8] of all types of lead–acid battery demonstrated that thirty commercial lead–acid designs were able to accept a rapid recharge. Moreover, valve-regulated lead–acid products responded particularly well and were capable of repeated rapid recharge for several hundred cycles. This advance has been achieved through careful attention to the charge algorithm and has been spectacularly successful to

Table 1
ALABC parameter targets and progress through the course of the 1990s

	Specific energy/range	Specific power[a] (W/kg)	Cycle life[b]	Recharge time	Purchase cost	Cost of ownership[c]
ALABC targets	50 W/kg, 100 + miles	150	500	50% — 5 min 80% — 15 min 100% — 4 h	$150/kW h	$0.085/mile
1992	25 W h/kg, 50 miles	150	75	100% — 8 h	$200/kW h	$1.12/mile
1995	35 W h/kg	150	500	50% — 5 min 80% — 15 min 100% — 4 h	$150/kW h	$0.113/mile
1998	48 W h/kg	150	800	50% — 3 min 80% — 10 min 100% — 30 min	$100/kW h	$0.05/mile

[a] At 80% depth-of-discharge.
[b] SFUDS cycles to 80% fall in initial capacity.
[c] Includes energy at $0.10/kW h.

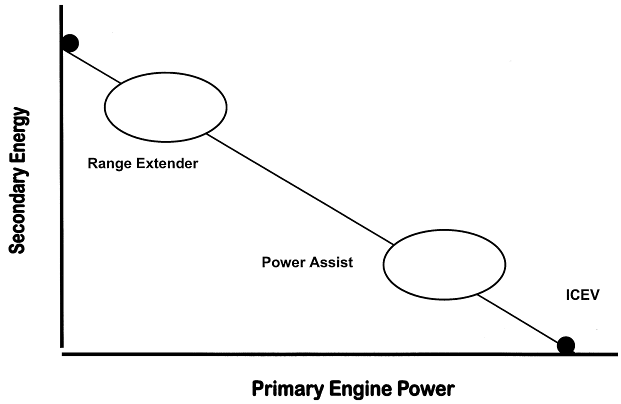

Fig. 3. Hybrid electric vehicle duty cycles for power assist (fast-response) and dual mode (slow-response) types.

the point that, in one vehicle study, a 50% charge is being returned in 3 min.

The capability for rapid recharge dramatically enhances public attitude towards the electric vehicle. It is widely accepted that most journeys for most people, on most days of the year, run for far less than 100 miles (160 km) (see Fig. 1) and any of the alternative candidate battery systems will be able to satisfy such journeys. The major concern over range relates to those few occasions in the year when the driver wishes to travel much greater distances, e.g., 300 to 400 miles (480 to 640 km). This requirement can only be satisfied by a system of rapid recharging. The lead–acid battery has been shown not only to be capable of such a rapid recharge but actually to benefit from it [10]. In an ALABC cycle-life test [8] performed on a commercially available, spiral wound, lead–acid battery, 250 cycles were achieved with conventional cycling while fast charging over a somewhat restricted state-of-charge range led to a cycle life of over 900. The fundamental mechanisms underlying the operation of the valve-regulated version of the lead–acid battery have been thoroughly studied and their influence on life performance are beginning to be understood. One of the important factors that has emerged is that high-rate charging preserves the high surface area of the active material [10,11]. Another important finding is that it is essential to minimize the time during which the battery is in gassing mode rather than the current passing during that time.

Improvements in the key parameters of the battery have been achieved through the 1990s, as shown in Table 1. Clearly, a product which, at the beginning of the decade, was not a viable energy-storage device for electric road vehicles has rapidly become acceptable as the present ALABC programme enters its final phase.

4. Batteries for hybrid electric vehicles — essential attributes

Major automobile manufacturers are evaluating hybrid electric vehicles as an alternative approach to the range/convenience issue. In the simplest terms, a hybrid electric vehicle is one with two separate power sources and very often these are a heat engine and an electric motor with some energy stored in a battery [12]. Two basic types of hybrid are under consideration.

(i) Series configuration: a small heat engine (for example, an internal-combustion engine) generates electricity which is fed into the battery/controller system so that the vehicle is driven exclusively by an electric motor (see Fig. 2).

(ii) Parallel configuration: either, or both, power sources can propel the vehicle.

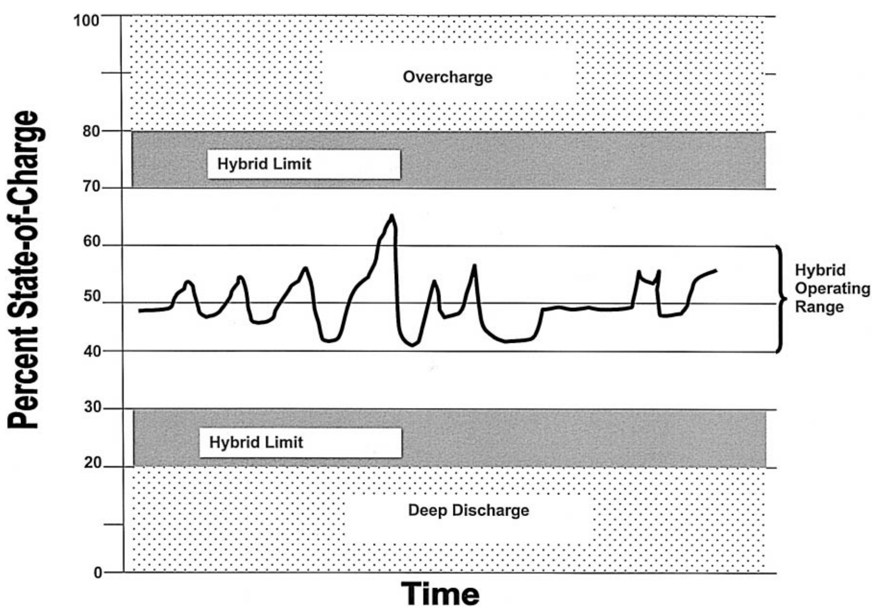

Fig. 4. State-of-charge limits for battery hybrid operation.

In both cases, the battery is smaller than for a pure EV. The battery in a series HEV is larger than that in a parallel HEV.

There are two broad duty cycles in which hybrid electric vehicles are envisaged to operate [13], as shown schematically in Fig. 3. The dual-mode (or slow-response) battery is relatively large and shares the power load more or less evenly with the primary source. It is most often used in a series configuration. The battery is cycled far more, but since it is larger than in the fast-response mode, the cycling is generally shallower. A further advantage is that since the larger battery has to capture essentially the same amount of braking and deceleration energies as that in the fast response mode, it will operate at a higher state-of-charge — a benefit in terms of both power and life performance. In the ‘‘power assist’’ (or fast-response) mode, the battery is called upon intermittently to provide added power and to take up regenerative braking or deceleration energy. The battery is relatively small in size and capacity. Because of this and the fact that it needs to capture as much braking energy as the larger battery in the dual-mode configuration, there is more of an emphasis on power and less on energy. The fast-response mode is often, but not always, the duty cycle anticipated for parallel hybrids.

A battery serving as the auxiliary power source in a hybrid electric vehicle is placed in a quite different duty cycle from that in an electric vehicle (see Fig. 4). It must operate continuously in a partial state-of-charge mode and must have the capability of furnishing and absorbing relatively high pulses of current in an irregular manner over a long calendar life. Moreover, the vehicle control system must be able to ascertain the battery state-of-charge and keep it in a fairly narrow operating range in order to prevent heavy overcharge or over-discharge. The requirements for the battery in a hybrid electric vehicle are thus significantly different from those for one in an electric vehicle. Nevertheless, the demand for a low purchase price is equally valid in the two cases.

Table 3
Characteristics of some high-power VRLA batteries

Battery	Size (A h)	Specific power (W/kg)	Specific energy (W h/kg)	$/kW h[b]
Bolder	1.2[a]	1000+	30	300
Optima	15	660	29	200
Electrosource	85	450	41	200

[a] 5 A h cells in development.
[b] Projected.

The minimum requirements for energy-storage systems for the two types of hybrid electric vehicle duty cycle (dual mode and power assist) have been set out by the Partnership for the New Generation of Vehicles (PNGV), see Table 2.

It is clear that, in these sorts of duty there is a much greater emphasis on the specific discharge power required from the battery than on the specific energy. This is because the vehicle relies primarily on the heat engine and hydrocarbon fuel for its energy supply and, hence, for its range.

5. How the valve-regulated lead–acid battery matches the requirements for hybrid electric vehicles

The very recent work on fast charging of VRLA batteries in connection with electric vehicle duty provides results which are very instructive in assessing the suitability for use of these batteries in the hybrid function. As noted above, VRLA batteries appear to respond to rapid recharge regimes better than flooded batteries. It is also clear that the best response is obtained from VRLA batteries with thin plates and low internal impedances. Low impedance is particularly important in controlling ohmic heating during

Table 2
Energy storage system performance goals set by the Partnership for New Generation of Vehicles (PNGV)

Characteristic	Units	Fast response engine minimum values	Slow response engine minimum values
Pulse discharge power (constant for 18 s)	kW	25	65
Total available energy (discharge plus regenerative)	kW h	30	70
Minimum round-trip efficiency	%	90	95
Cycle life, for specified SOC increments	cycles	200 K for 25 W h, 50 K for 100 W h	120 K for 100 W h, 20 K for 600 W h
Maximum weight (plus marginal increase per unit of energy > 3 kW h)	kg	40	65 (+1 kg/kW h over 3 kW h)
Maximum volume (plus marginal increase per unit of energy > 3 kW h)	1	32	40 (+8 l/kW h over 3 kW h)
Production cost, at 100,000 units per year (plus marginal increase/W h for marginal increase of energy > 3 kW h)	$	300	500 (+$62.50/kW h)
Operating voltage limits	Vdc	300 min, 400 max	300 min, 400 max
Max allowable self-discharge rate	W h/day	50	50
Operating temperature range	°C	−40 to +52	−40 to +52

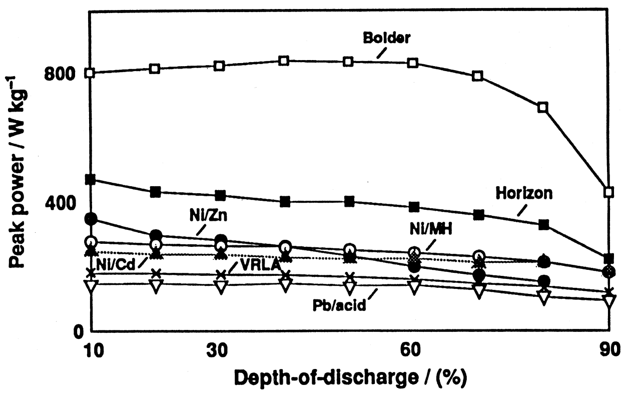

Fig. 5. Peak power as a function of depth-of-discharge for a spiral-wound VRLA battery and several other types of batteries (Ref. [12]).

fast charging. Further, some substantial benefits are to be gained by operating over a limited range of depth-of-discharge, a duty which extends the cycle life dramatically [8,14]. From these observations, it can be deduced that VRLA batteries with thin plate designs and low impedances may well be good candidates for operation in hybrid electric vehicles. Characteristic performance data of promising VRLA batteries are shown in Table 3. Recent studies have demonstrated that a spiral wound battery with very thin plates [15] and a quasi-bipolar design can both sustain very high levels of peak power to a substantial depth-of-discharge (Fig. 5) — performances which far outstrip those of other battery systems. It seems likely that, with some specialist development, the suitability of these lead–acid products for hybrid electric vehicles can be enhanced still further without losing sight of the cost advantage that generally attaches to lead–acid batteries.

6. Conclusions

During the 1990s, the valve-regulated lead–acid battery has been developed intensively for electric vehicle applications to the point where the cycle life has been improved by a factor of about 10, the specific energy by a factor of almost 2, and the recharge time has been reduced by around an order of magnitude. This advanced technology now appears promising for development into a low-cost option for hybrid electric vehicles. Some further attention may have to be paid to maximizing the cycle life of the system in the HEV duty cycle. The overall mix of battery electric vehicles, hybrid electric vehicles and fuel cell electric vehicles in future transport fleets remains the subject of much conjecture. It is likely that there will be opportunities for all three systems and that the advanced valve-regulated lead–acid battery will be the favoured means to store energy and/or to provide power in many of these vehicles.

References

[1] Electric Vehicle Vision 2007, EPRI TR-109194, October, 1997.
[2] K. Smith, K. Morgan, Progress Report 2, ALABC Project AMC008, 1998.
[3] I. Baeringer, Progress Report 1, ALABC Project A005.3, 1998.
[4] L. Albert, A. Chabrol, L. Torcheux, P.H. Steyer, J.P. Hilger, J. Power Sources 67 (1997) 257.
[5] R.H. Newnham, W.G.A. Baldsing, M. Barber, C.G. Phyland, D.G. Vella, L.H. Vu, N. Wilson, Final Report, ALABC Project AMC007, 1998.
[6] A.F. Hollenkamp, J. Power Sources 59 (1996) 87.
[7] P.T. Moseley, J. Power Sources 67 (1997) 115.
[8] T.G. Chang, D.M. Jochim, J. Power Sources 64 (1997) 103.
[9] E. Meissner, E. Bashtavelova, A. Winsel, ISATA Proceedings, 97 EL066, 1997.
[10] L.T. Lam, H. Ozgun, O.V. Lim, J.A. Hamilton, L.H. Vu, D.G. Vella, D.A.J. Rand, J. Power Sources 53 (1995) 215.
[11] I.M. Steele, J.J. Pluth, J. Richardson, N. Zaluzec, A. Hollenkamp, Progress Report 1, ALABC Project B-004.1, 1997.
[12] D.A.J. Rand, R. Woods, R.M. Dell, Batteries for Electric Vehicles, Research Studies Press, Taunton, UK and Wiley, New York, 1998.
[13] R.F. Nelson, Final Report, ALABC Project B013.1, 1998.
[14] R.H. Newnham, W.G.A. Baldsing, J. Power Sources 59 (1996) 137.
[15] T. Juergens, R.F. Nelson, J. Power Sources 53 (1995) 201.