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Journal of Power Sources 116 (2003) 118–127

www.elsevier.com/locate/jpowsour

Assessment of high power HEV lead-acid battery advancements by comparative benchmarking with a European test procedure

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Abstract

The technical and practical suitability of lead-acid batteries for applications in vehicles with electrical drivetrains (battery-powered or hybrid electric) has been experimentally investigated in a variety of testing programmes. Under the direction and funding support of the Commission of the European Community, since early 1990s, the R&D Organisation EUCAR, a collaborative partnership of most European car manufacturers, has been conducting battery technological assessment projects, through bench tests carried out by different independent laboratories throughout Europe, using agreed test procedures. In this framework, ENEA acted as independent testing institute and tested, among others, three high power lead-acid batteries of various technologies (flat plate electrodes and spiral wound) for EV and HEV applications. In addition, different battery sizes and operating conditions have been tested at ENEA in a separate collaboration with ALTRA-IRISBUS.

This paper intends to trace technological and performance improvements of high power lead-acid battery technology through the analysis of experimental data during parameter and life cycle tests, including the effects of battery sizes, charge/discharge profiles and testing procedures, with special emphasis on the reduction of the internal resistance and the variation of peak power and cycle life.

Keywords: Lead-acid; Battery; High power; Hybrid electric vehicles; Testing procedures; Technology development

1. Introduction

The progress of automotive engineering is requiring new and diversified functions for the onboard energy storage systems. Storage electrochemical batteries, and even supercapacitors, are researched and developed in a variety of chemistries and configurations to better meet the continuously changing technical and economical requirements for battery-powered electric vehicles (EVs), hybrid electric vehicles (HEVs), and even conventional internal combustion engine vehicles (ICEVs) with 42 V electrical chain. As a consequence of these changes, the lead-acid battery industry has been producing more specialised products with dedicated performance characteristics for the various automotive applications. In particular, in recent years the lead-acid battery technology has been largely modified to improve high power performances and meet specific requirements of HEV applications.

In more than 10 years, the R&D Organisation EUCAR of many European car manufacturers (BMW, Fiat, Daimler-Chrysler, Opel, PSA, Renault, Volkswagen, Volvo) has been investigating, under the direction and funding support of the Commission of the European Community (EC), through an experimental and practical approach the commercial and under development energy storage technologies (battery and supercapacitors) for battery-powered (EVs) and hybrid electric vehicles (HEVs). Many projects have been funded until now, with the last one (ASTOR), started on April 2001 and lasting 36 months. One of the fundamental results of those projects has been the definition, in collaboration with many independent European testing institutes, of a set of testing procedures [1,2], which have been applied to experimentally assess and compare energy storage performances and properties in different vehicular applications. The results are of high value and quality for the EUCAR members [3], because they can establish their investment plans and may create competition among component manufacturers, by directing their efforts towards car makers needs.

According to the distribution of the work among EUCAR members, FIAT Research Centre (CRF) has always had the

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doi:10.1016/S0378-7753(02)00715-2

responsibility of lead-acid battery technology and relied on ENEA (Italian National Agency for New Technology, Energy and the Environment) Battery Test Laboratory to perform the actual tests. ENEA has been testing various lead-acid batteries for EV and HEV applications in EUCAR projects: in particular, since 1997, three high power lead-acid battery systems of various manufacturers have been tested for EV and HEV applications.

On the other hand, since the mid-1980s, ENEA has been conducting large testing programmes also in collaboration with component manufacturers and vehicle makers of EVs and HEVs in its testing laboratories to support technological development and to facilitate the introduction of electrically-powered vehicles. In particular, during the past year, in collaboration with ALTRA-IRISBUS, one of the largest European manufacturers of trucks and buses, two high power lead-acid batteries to be applied in a hybrid bus for urban transport have been tested.

In total, four high power lead-acid batteries, differing in technology (flat plat, absorptive glass mat-AGM electrolyte, spiral wound), in production time, in size and even in assembling and control systems are carefully compared in this paper. Furthermore, the effects of EUCAR test procedures [1,2] are experimentally studied, along with a life cycle profile slightly modified at ENEA, during the tests for ALTRA bus batteries, in order to fit the charge and discharge profile to a more realistic driving pattern for an urban bus in actual road operations (more than 230 km per day at temperatures close to 40 °C).

2. Lead-acid test samples and procedures

In the framework of the EC contracts, several lead-acid batteries from different companies have been tested. Different sizes of modules have been assembled in battery packs, from 24 to 85 Ah, suitable for all the designs of electrical traction systems, from full electric to hybrid electric vehicles.

Different technologies have also been considered: modules with traditional thick flat plates for high energy uses (full electric traction); thin flat plates with pure lead grids, for high power and low corrosion performances (high power and deep cycles); spiral wound electrodes for high surface and high specific power. In addition, a very small battery, 1.2 Ah was also tested with electrical characteristics similar to a double layer capacitor. These batteries were tested in various laboratories throughout Europe. Other similar batteries were also tested at ENEA as a result of collaborations with vehicle manufacturers and battery developers.

2.1. Test samples

Table 1 summarises the main basic properties of the four high power batteries, tested at ENEA, whose experimental results are considered for the comparative assessment for various generations of lead-acid technology. All the batteries were commercial products, procured on the market. In some cases, the batteries were supplied by the manufacturers in a special assembly to better fit the testing requirements: dedicated chargers, control systems and case with thermal conditioning were in some cases included in the configuration.

The EU1 was a valve-regulated lead-acid (VRLA) battery with starved electrolyte. The technology is a gas recombinant type using an absorptive glass mat (AGM) separator for absorbing the electrolyte, pure lead grids and thin flat plates for high power applications: the modules were originally developed for and used in aircrafts. The test sample was a 108 V battery system composed by nine modules with special intra-modules separators made by a plastic case filled with phase-change material, and a metallic container, enclosing series-connected modules as a single unit. The version supplied for the test was exactly the commercial one, while the assembly, the connections, the wiring and the sensors installation were specifically developed for EVs.

The EU2 was a VRLA technology using a spiral wound technology. Each individual cell contains only two plates, one positive and one negative. These thin pure lead plates are wound into a tight spiral and separated by an AGM layer. This material is very thin allowing for the lead plates to be closer each other. The close proximity of the lead plates enhances the flow of electrical current and lowers the batteries internal resistance for higher power levels. The system was assembled in a 144 V configuration with 12 series-connected modules, and supplied with a battery charger and a battery management system (BMS). Furthermore, each module was equipped with a module equaliser with the scope to reduce cell unbalancing during charging.

The EU3 and AL1 were again VRLA batteries with the electrolyte absorbed in an AGM separator and with thin flat

Table 1
Basic properties of the tested lead-acid battery samples

Battery reference number	Testing period	System weight (kg)	System volume (l)	System voltage (V)	Rated capacity C_5 (Ah)	Rated energy at C_5 (kWh)
EU1	1997	51.9	96.5	108	26.0	2.8
EU2	1997–1998	289	192.0	144	52.0	7.5
EU3	1999	107.3	33.3	108	26.0	2.7
AL1	2001	219.6	89.1	108	70.0	7.6

The EU*n* number identifies the systems tested in the EC projects, while the AL1 battery refers to the system for the ALTRA hybrid urban bus.

Table 2
General test sequence for on-bench battery evaluation

Test type	Description
Initial inspection	Visual inspection and physical parameters determination (weight, volume)
Electric formation	Minimum set of charge/discharge cycles to verify and homogenise module properties
Parameter check-up (self-discharge, constant current discharge, dynamic cycles (ECE-15), internal resistance, OCV + CPP)	Periodic control of basic parameters. After a defined number of life cycles, the check-up allows for verifying decline of basic performance characteristics (storage capacity, internal resistance, power capability and self-discharge)
Life cycle test	A defined profile composed by a sequence of ECE-15 (urban and/or extra urban parts) power cycles, idle time and charging period
Final inspection	Control of the status of the battery at the end of the test sequence, when termination criteria are reached and the final parameter check-up is completed

OCV, open circuit voltage; CPP, calculated peak power.

plate electrodes in lead and tin alloys. Thin grid technology allows for very high power rates, while lead–tin alloys (with calcium and antimony) in the grid limit the corrosion in deep discharge operations. The battery would then be suitable for high power and deep discharge profiles. The tested samples were both assembled in a 108 V battery system composed by nine 12 V modules, series connected without any case or tray. The main difference between the two systems was the storage capacity: 26 Ah for EU3 and 70 Ah for AL1.

2.2. Test procedures

The EU batteries were tested using the procedures for life testing in EVs and HEVs applications [1–3], defined by the EUCAR group. In particular, Table 2 reports the general test sequence applied to all the samples.

The main differences among the test sequences applied to the four batteries were in the life cycle test profile. In fact, the driving profile used in the life cycle (ageing) test on the bench is referred to either a pure electric vehicle (only battery-powered) or else a hybrid series configuration where an auxiliary power unit supplied a constant power to the batteries in order to recharge them continuously during the service. This situation is simulated on the test bench by a battery power profile simulating the battery behaviour during a driving pattern to be performed by the EUCAR reference vehicle (Table 3) and, in our case, by the ALTRA urban hybrid bus:

1. The EU1 and EU3 batteries were life cycle tested with a dual-mode high power profile, in which the reference hybrid vehicle (with pure electric mode) is powered by the battery only until the battery state-of-charge (SoC) is >40%. For lower values, an auxiliary power unit (APU), a thermal generator, is switched on to supply 4.4 kW to recharge the battery and power the vehicle. The overall life cycle profile includes a sequence of ECE-15 power profiles, composed by an urban and extra urban part [3], up to the completion of 10 complete cycles (corresponding to 113 km of travelled distance) and a pause and charging period. Fig. 1 shows the battery SoC during a dual-mode high power life cycle test.
2. The EU2 battery was cycled with a profile composed by a sequence of ECE-15 power profile (until 20% SoC was reached), a pause and a charging mode. The test profile simulated a pure electric mode of the EUCAR reference electric vehicle.
3. The AL1 battery was tested with a life cycle profile similar that of the EU1 and EU3 batteries, simulating a series hybrid vehicle, but using only the urban part of the ECE-15 power profile and with power values adapted to more realistic operating conditions. The daily real operating condition was simulated on the bench repeating 16 times a cycle, composed by 17 ECE-15 power profiles (only urban part) for a total travelled distance of about 272 km per day.

Table 3
Main characteristics of the EUCAR reference vehicle

Properties	Value
Gross weight (in kg; including batteries)	1150
Rolling resistance (kg/t)	10
Air drag coefficient, C_d	0.33
Frontal area (m^2)	1.8
Average drivetrain efficiency (%)	65

2.3. Test equipment

All the tests on the four batteries were carried out in a dedicated battery test facility, located at the ENEA Casaccia Research Centre. This facility is part of a unique network of testing laboratories, including a supercapacitor test rig, a drivetrain laboratory and a roller dynamometer facility. The specific equipments used during the tests are summarised in Table 4.

The climatic chamber was fundamental in controlling battery temperature during the tests. In general, life cycle testing was carried out at room temperature (23 ± 2 °C, stated by the climatic chamber). For the AL1 battery, the battery temperature was varied (at 33 and 40 °C) to investigate the effect on battery characteristics: the temperature values came out from a direct measurement of the battery temperature during an urban hybrid bus demonstration.

Table 4
Battery testing equipment at ENEA

Type	Built by	Ratings	Remarks
Battery cycler E-8376	ELTRA	0–330 V, ±400 A	Fully programmable; purpose developed
Data logger 500a	Keithley		Fast varying voltage and temperature measurements
Climatic chamber UY 2250 SP	Angelantoni Climatic Systems	−40 °C, +100 °C	Large volume (2250 l); temperature stability ±0.5 °C

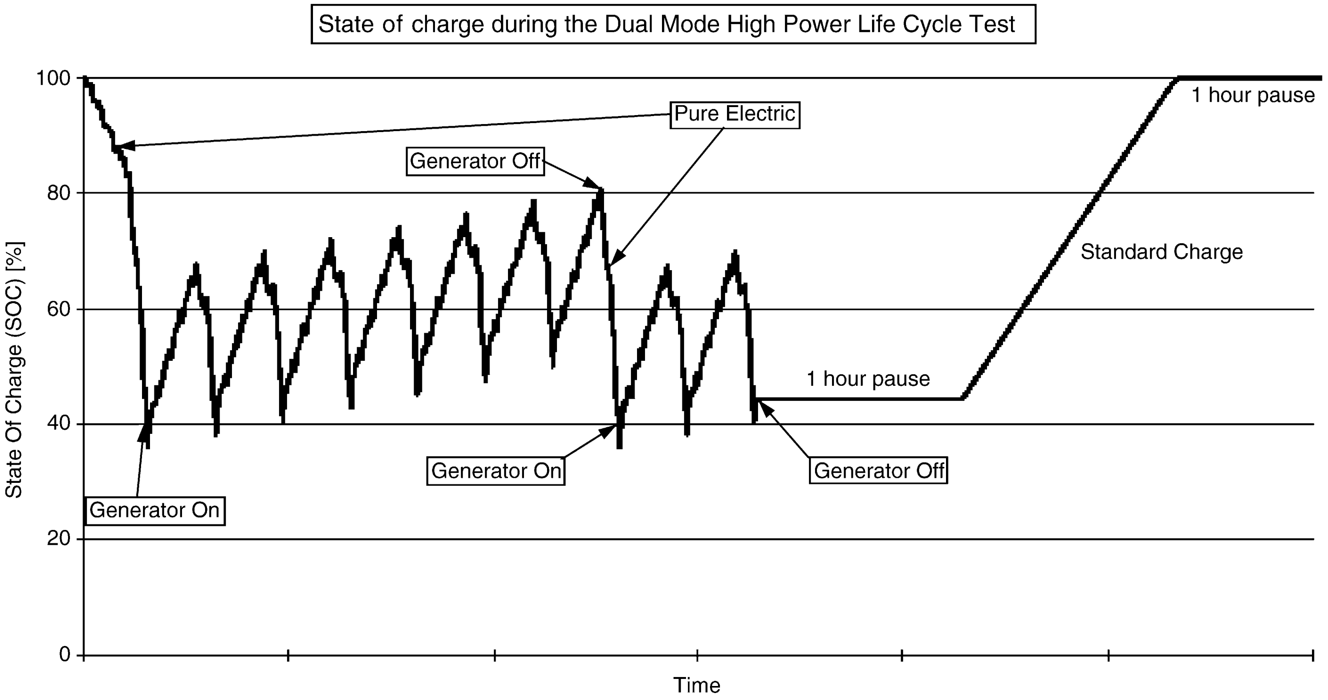

Fig. 1. Battery SoC during dual-mode high power life cycle test.

Experimental data have been directly recorded by the ELTRA cycler, controlled with an IBM PC, and by a Keithley data logger. Each battery was equipped with many sensors to measure: overall current, total and module voltages, and T-type thermocouples for mapping the temperatures in various points of the battery systems. Module voltages and temperatures values were acquired by the Keithley data logger. Dedicated data acquisition and control software were available: ELTRA S276_33 for the battery cycler and EASYEST LX for the Keithley 500a.

3. Test results

The comparative assessment is mainly based on the analysis of battery performance characteristics of specific interest for high power applications in HEVs and their variations with the technology, the environmental conditions and the ageing profiles:

1. Specific peak power, power to energy ratio (*P*/*E*) and internal resistance at various depth-of-discharge (DoD).
2. Storage capacity and specific energy at a defined discharge mode.
3. Overall delivered energy and total range in pure electric mode.
4. Voltage dispersion and thermal behaviour.

All these parameters are of high value in designing and optimising the battery technology, the battery use and the integration in specific HEVs.

3.1. High power performances

The EUCAR reference vehicle requires at least 250 Wh/kg at 60% DoD and, consequently, a very low internal resistance during discharge. In addition, the storage capacity in dual-mode operation must be sufficiently high to assure an adequate pure electric range, stable over the cycling to assure a long cycle life (and an acceptable operating cost). Finally, the specific values (energy and power per unit mass and volume) must be high enough to limit the share of vehicle mass and volume occupied by the battery.

Fig. 2 shows the variation of specific peak power at beginning and at the end of the life cycling in correspondence of two DoD values (the values for EU2 are not completely significant because the discharge current was limited at 150 A for assembly restrictions). It is apparent that, apart from the

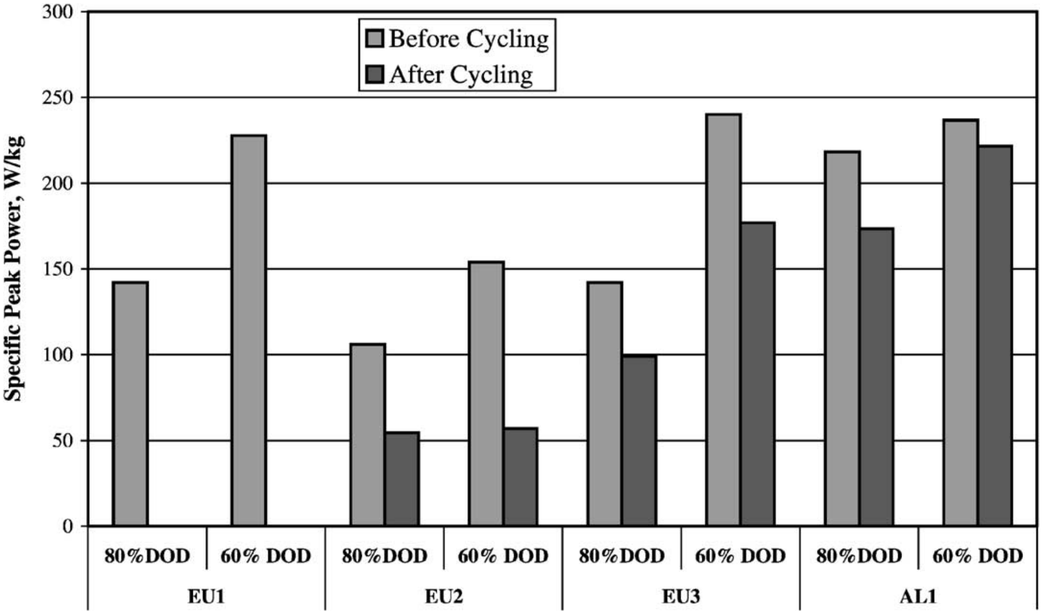

Fig. 2. Specific peak power at various DoD and at beginning and at the end-of-life cycling.

impossibility of the EU1 battery to reach 60% DoD during power tests, there are significant variations among the first two and the last two batteries. In addition, the EU3 and AL1 batteries of the same technology, but different size, show improvements with the increase of size: higher specific power and lower power decline after a modified life cycle test.

For completeness, the technical requirements for high power batteries in HEV applications require an extremely varying ratio (*P*/*E* in W/Wh) of two basic parameters: peak discharge power (*P*) and overall energy content (*E*). From pure EVs to various HEV configurations (minimal hybrid, integrated-starter-generator (ISG), range extender, dual-mode, power assist), this figure of merit *P*/*E*, introduced in recent years [4], can vary from 1–4 up to over 100 W/Wh. The *P*/*E* values of the four tested batteries are very close each other (7–9 W/Wh), but quite far from the values required by the technical targets of the Office of Automotive Transport Technologies of the US Department of Energy (OATT) High Power Battery Programme: 27 W/Wh for dual power mode and 83 W/Wh for power assist.

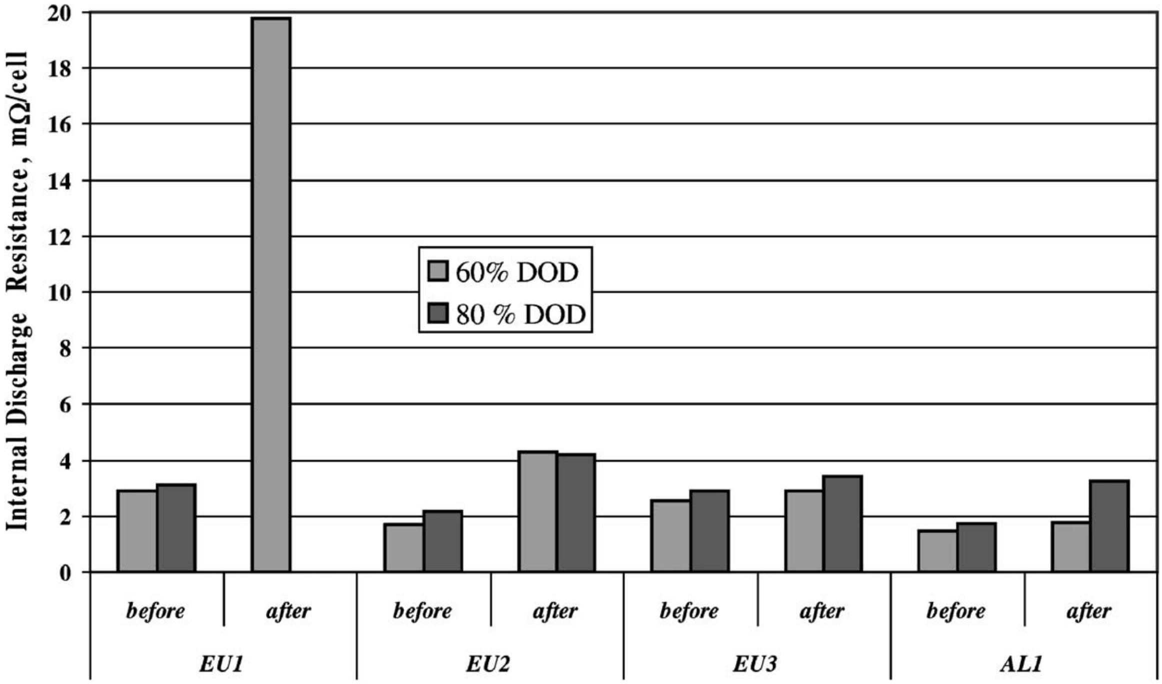

Fig. 3. Variation of the internal resistance during discharge at various DoD and before and after cycle life tests.

The behaviour of high power batteries with technology and cycle life finds a direct confirmation of peak power trend by comparing the increase of the internal resistance during discharge. Fig. 3 shows how the internal resistance changes over the technology and the tests.

The EU1 (1996 battery technology) seems clearly not well suited to the specific power requirements for HEVs. Moreover, the EU3 and AL1 batteries present close characteristics, suggestive of a well-developed production process, which determines stable and reproducible physical and chemical properties: differences may be due to variations in the assembly.

3.2. Specific energy, overall energy throughput and travelled distance (ageing over cycles)

With respect to EV lead-acid batteries, high power batteries greatly differ in construction and assembly. These batteries were purposely developed to supply the rated power (and even enough energy for a pure electric range) for a large number of cycles in order to meet technical and economical HEV requirements. The four tested lead-acid batteries are really representative of the lead-acid industry efforts to diversify functions and characteristics, still maintaining adequate reliability and cycleability. Table 5 summarises overall cycling data: travelled distance and life cycles.

Further details of energy data stability are reported in Fig. 4, which shows the specific energy behaviour over cycling. According to these results, the last generations of high power lead-acid batteries seem to be more responsive to the specific technical requirements of HEV applications with limited deterioration of basic performances. The end-of-life reasons were mainly related to early failures of some modules.

3.3. Thermal, control and assembly considerations

The high power requirements for HEV applications have obviously justified the development of new design and control systems, able to minimise thermal gradients in the

Table 5
Life cycle energy data for the four batteries

Battery reference number	Testing period	Total number of life cycle profiles	Energy throughput over test (kWh)[a]	Travelled distance per reference vehicle (km)
EU1	1997	52 (Dual-mode HEV)	321	5.500
EU2	1997–1998	115 (Pure EV)	134	7.271
EU3	1999	101 (Dual-mode HEV)	771	11.630
AL1	2001	101 (Dual-mode HEV modified for bus)	–	27.472

[a] The overall energy delivered by the battery during the complete test sequence.

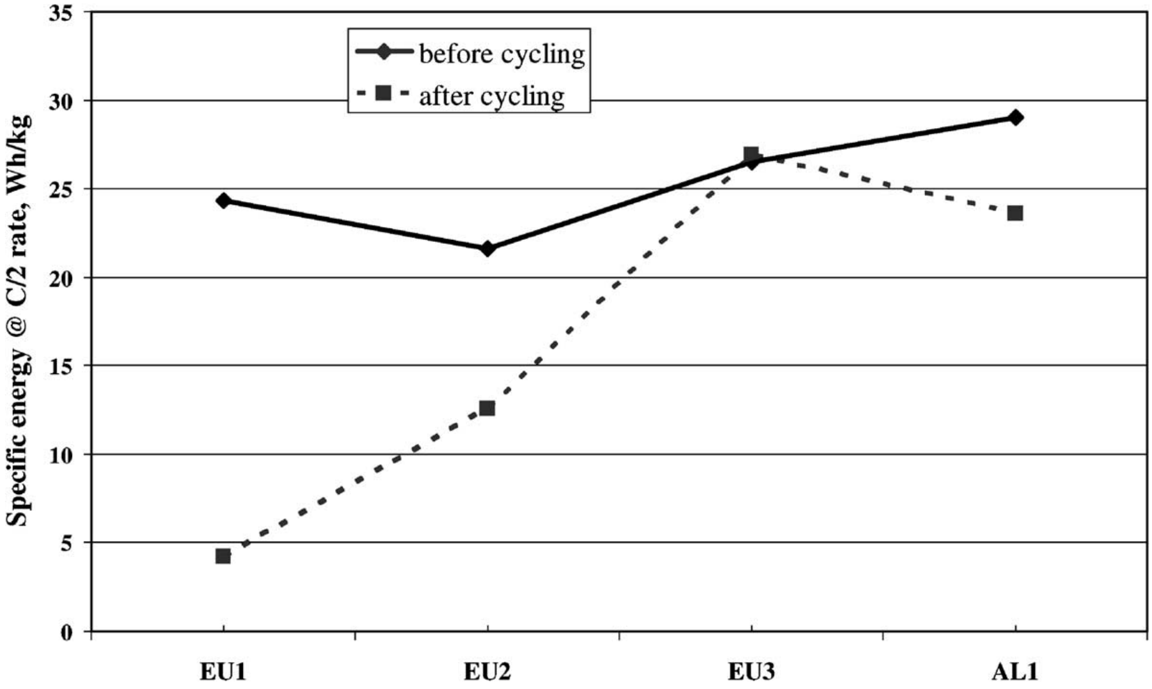

Fig. 4. Specific energy at C_2 rate for the four batteries over cycling.

battery system and voltage dispersion among modules (monoblocs). The four batteries tested at ENEA were assembled in various manners to tackle such problems and were even equipped with dedicated equipment to monitor and/or control module temperature and significant variations among module voltages, able to accelerate failures of

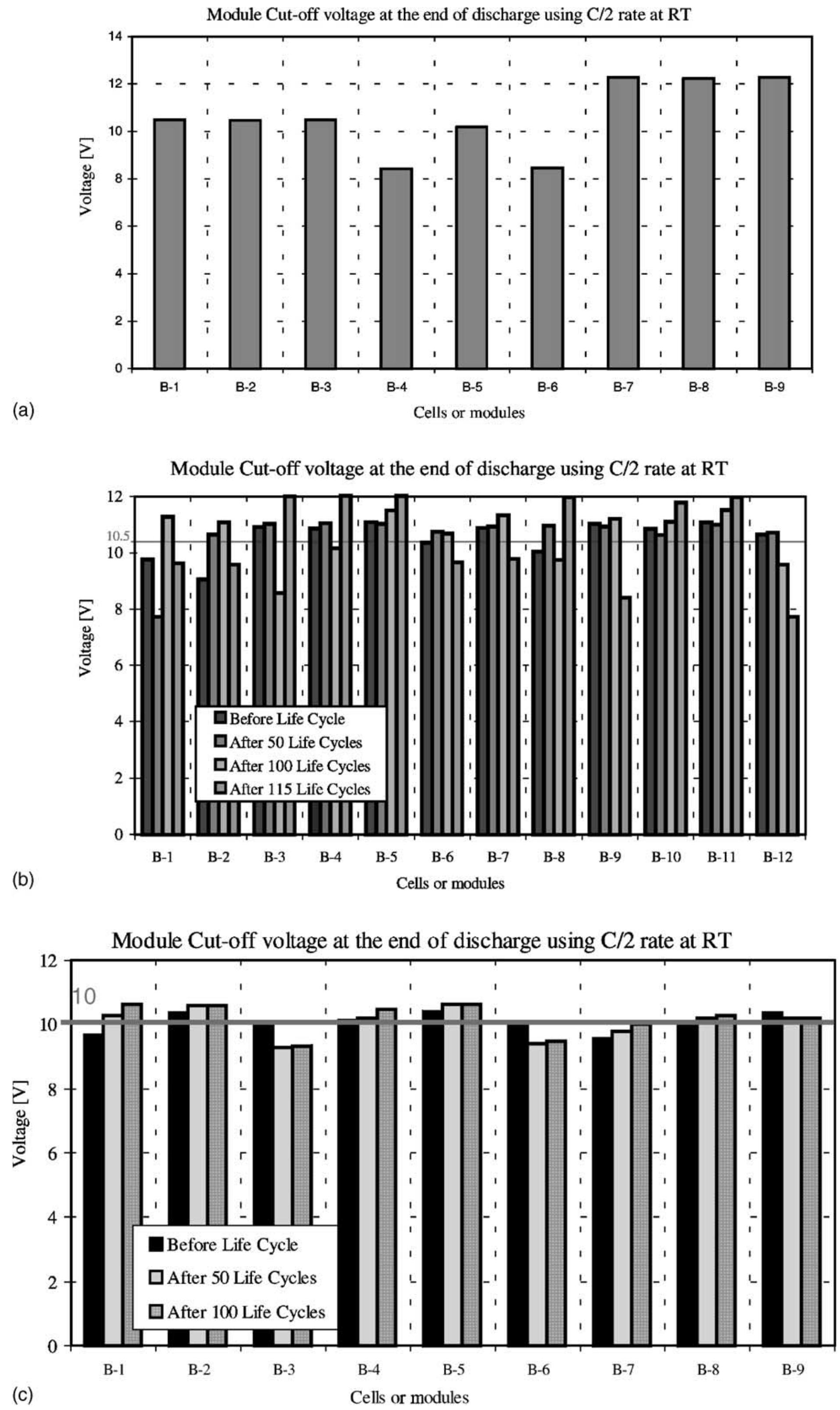

Fig. 5. Module voltages for: (a) EU1 battery; (b) EU2 battery over cycling; (c) EU3 battery over cycling. For AL1, the behaviour is similar.

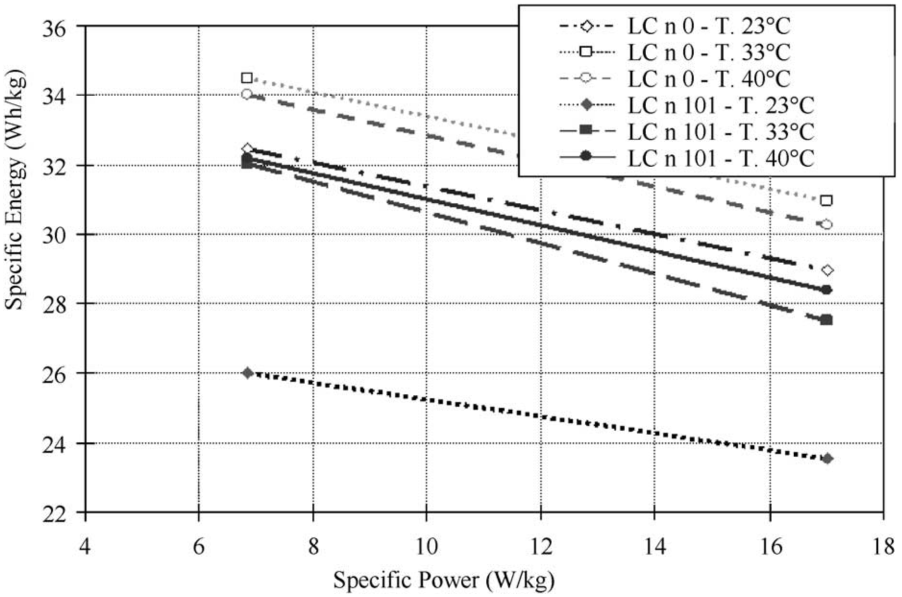

Fig. 6. Ragone plot of AL1 at various temperatures and test cycle.

weaker modules. In particular, EU1 was equipped with temperature stabilisers, located among modules, with the scope to absorb excess heat by favouring the change of phase of a special material; EU2 had local passive charge equalisers (on each module) in order to minimise voltage dispersion. In common, there was a well-defined spacing among modules (with or without containment case) and a particular attention to the charging profile and the equalisation procedure to limit negative thermal and dispersion effects. Fig. 5a–c describes the module cut-off voltages at the end of discharge over cycling.

The voltage variation among modules was one of the major reasons responsible for early failures of some modules and, at the end, justified the end of tests, because the end-of-life criteria (available capacity or specific power) were reached. One peculiar feature of HEV operations is that the battery is normally cycled in a DoD window (in dual-mode operation is between 60 and 20%, while in a power assist mode the DoD variation is 5% at 40% DoD). These operation modes prevent to equalise modules at the end of each cycle with a defined charging profile. A way to try to minimise this detrimental effect was the application of

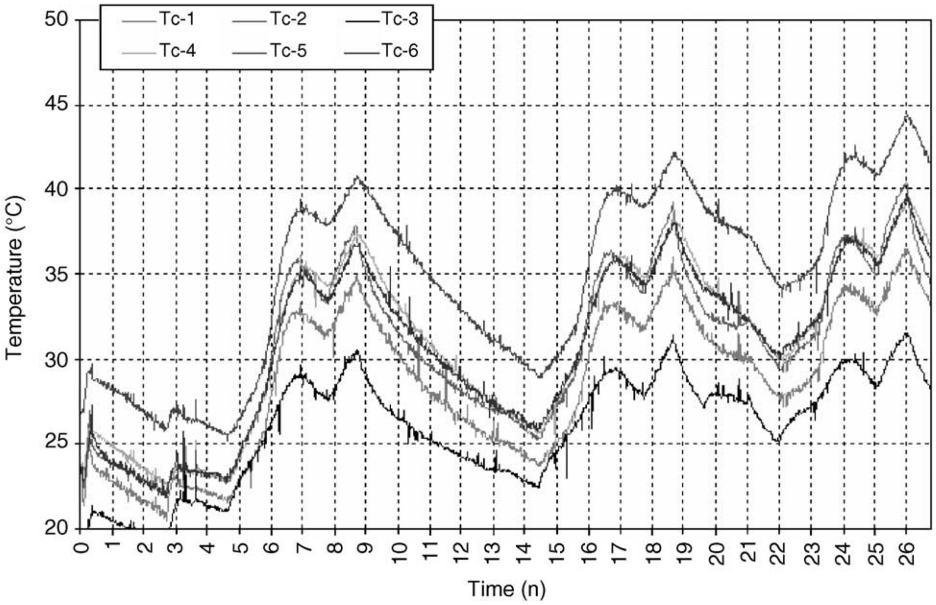

Fig. 7. Temperature gradient in AL1 system at the end-of-life cycling.

periodic procedures to equalise module voltages and state-of-charge and reduce voltage dispersion. Fig. 5 demonstrates the efficacy of such equalisation steps.

In addition, it is equally important to avoid significant temperature gradients among modules exceeding temperature limits in some points of the system. The batteries under test had a maximum temperature limit of 50 °C (only EU2 was recommended at 60 °C). Temperature gradients and, consequently, limits exceeded locally must be carefully avoided: temperatures extremely affect lead-acid battery performances and life (temperature is normally used as an acceleration factor in life testing). Usually, any type of battery undergoes thermal stresses during charging and equalisation processes and requires some sort of thermal control, but in high power applications as in an HEV, the high power levels motivate the introduction of more efficient thermal management systems able to rapidly cool down the modules, still maintaining a small temperature gradient among monoblocs. Of course, the proposed solutions must be technically feasible and cost-effective in order to limit architecture complications, hardly managed in an automotive environment, and to increase battery system costs, which may not be acceptable to manufacturers and end users. Fig. 6 shows the specific performance variation with the temperature of AL1, while Fig. 7 shows the temperature gradient in AL1 systems at the end-of-life testing.

Similar behaviours were obtained with all the batteries under test, with an increasing uniformity of temperature rise among modules from EU1 to AL1. In some cases, the temperature rise was very close to the recommended limits, showing inadequate thermal management solutions (e.g. the use of phase-change thermal stabilisers).

4. Conclusions and future work

The comparison of experimental results of four different high power lead-acid batteries (with spiral wound grids in pure lead, flat plate with alloys, AGM recombinant systems), tested in EUCAR and ENEA projects, and developed and designed in recent years, is demonstrative of the progress and the efforts carried out by the battery industry to meet ever more demanding power performances of batteries in automotive applications. The continuous modifications of technical and economical requirements for high power batteries in HEV applications (from minimal hybrid up to full hybrid configuration with a significant pure electric range) have motivated the development of new lead-acid technologies that have also to compete with new and emerging electrochemical storage batteries, such as lithium or nickel–metal hydride.

Preserving the peculiar feature of a low cost and well-consolidated technology with already existing recycling chains, the lead-acid batteries have been improved in fabrication processes and even in handling procedures (assembly, charging profiles, thermal management and so on). The experimental activities carried out at ENEA, in the framework of EUCAR projects, and in collaboration with ALTRA, have verified that:

1. The sensitivity of the various technologies to the testing procedures, the life cycle profiles and the various operating conditions is well defined: the first generations of high power batteries (EU1 and EU2) seemed to be at a prototype level with performances and handling procedures not yet well suited for HEVs. EU3 and AL1 batteries took advantages of the EUCAR experiences and the clear definition of technical requirements and testing specifications to optimise high power performances. The number of life cycles improved from 52 to 101 cycles, and the distance travelled before the battery substitution changed from 5500 up to over 27,000 km.
2. The assembly and the control mechanisms (even quite sophisticated) presented limitations and needs for further improvements. The main issue will be to have a compromise between effective control and cost. Thermal management will be an issue: the use of a powerful climatic chamber in ENEA laboratories may have, to some extent, underestimated the impact of environmental temperatures over battery performances and life. The proposed solutions for temperature control and voltage dispersion limitations seemed not yet adequate for use in an HEV.
3. The battery size (EU3 and AL1) did not affect significantly the battery behaviour: as expected, the life cycle profile has much more influence on battery life and behaviour.

The high power lead-acid batteries needed to be further improved to expand their application possibilities in automotive hybrid configurations. The current trend of automotive industry to separate functions (with *P*/*E* ranging from 1 to almost 100 W/Wh) of the onboard battery storage requires increased specialisation of the batteries to such a diversified world. The lead-acid battery improvements, as well as for other battery types in competition with lead-acid (mainly, lithium and Ni–MH batteries), should be supported by the development of more adequate thermal and control systems, and also more specialised charging and equalisation procedures.

From the car manufacturers and testing institutes side, there is a continuation of efforts and an increased collaboration with the battery industry. The testing procedures are continuously updated and adapted to the new usages (42 V, minimal hybrid with integrated-starter-generator configuration). Furthermore, testing projects are continued in Europe by the EUCAR partnership, with the support of the EC: the project ASTOR, started on April 2001 and lasting 36 months, includes the assessment and testing of high power storage devices (batteries and supercapacitors) and the development or update of testing procedures [5]. In addition, testing activities, along with research projects on control devices (and algorithms) and state-of-charge indicators, will be also continued at ENEA in collaboration with the battery and car industry.

Acknowledgements

The present work is the result of a variety of projects carried out since mid-1990s. One of the authors (CRF) wishes, first of all, to acknowledge the financial support and the strategic direction of the European Commission, in particular of the Research Directorate-General, given to the EUCAR partnership; and, jointly with the other authors, the invaluable contribution of EUCAR members in defining testing procedures and assisting in data analysis. In addition, ENEA authors wish to thank ALTRA-IRISBUS for the collaborative support during the test work on AL1 and for permitting the use of the experimental results.

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