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Comparative study for "36 V" vehicle applications: advantages of lead-acid batteries

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Abstract

From thermal engine equipped vehicles to completely electric ones, evolution of light weight vehicles in the future will take several steps in so far as there is no adequate battery or fuel cell presently available to power these vehicles for "on the road" driving. On the other hand, for city driving, vehicles can be improved a lot in terms of fuel efficiency as well as air pollution, if partly or totally electric propulsion can be developed, manufactured and marketed for appropriate applications.

The 36–42 V battery is part of this orientation towards improving the efficiency of thermal vehicles in city driving, while keeping adequate autonomy on the roads. Actually, in city traffic, thermal engines are idle most of the time and stop periods represent a large part of the time spent "driving", using up fuel and polluting air for no use at all. The idea of stopping the engine during these periods, if appropriately managed, might potentially lead to a large improvement in fuel economy as well as air pollution reduction. The association of a higher voltage battery to an alternator–starter device in thermal vehicles, seems to be an interesting way towards that end.

In this paper, we are presenting our results of a study we have just completed in relationship with RENAULT & VALEO, supported by the French Ministry of Industry, concerning a comparative evaluation of different automobile energy storage systems, and the definition of specifications as the final step of this study. The main conclusion is that lead-acid will still remain dominant in this role, since its operational cost versus efficiency is by far the lowest of every battery presently considered, more particularly in the less expensive car segments.

Keywords: Lead-acid battery; 36–42 V application; Electrical power supply; Batteries comparative study; Batteries for starter–alternator; Stop & Go functions.

1. Introduction

Due to air pollution increase in over-crowded European cities, as well as to a fuel efficiency decrease for cars cruising in these areas (*traffic jams, stop lights, average speed, etc.*), a dramatic improvement of the situation could be achieved if partly electric vehicles could be developed and proposed to people driving mainly in these cities, eliminating the fear of running out of electricity encountered with purely electric vehicles. Since no adapted battery can fulfil the expectancy of customers with purely electric vehicles, it seems that, at least in the short term to medium term, no other solution exists other than proposing partly electric vehicles, still having a thermal engine for longer trips that the customer is expecting to be able to make, occasionally.

For partly electric vehicles, several technical architectures can be devised and vehicles can be partly electric in different ways. It can either be through

- the "Stop & Go" function that one can expect to use in the near future;
- an electrically assisted propulsion (*booster system*);
- a hybrid propulsion (*thermal and electrical propulsion with various degrees of one or the other*);
- a purely electric propulsion (*the thermal engine providing electricity to recharge buffer batteries*).

  Ultimately, purely electric vehicles, probably using a battery associated to a fuel cell, the latter for range reasons, or a fuel cell alone if power requirements are met with this system.

But, other possibilities are also being considered and evaluated: compressed air systems, micro-turbine/alternator associations, fly wheels, etc. and no real single solution seems to win the battle yet.

Considering the near future, for which our company is facing possible changes in the products to supply the car manufacturers, this study was more particularly devoted to the evaluation of the several energy storage technologies presently available at EXIDE and around the world. This evaluation was focused on the short term

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application in cars, which we think is the "Stop & Go" function.

In the present article, first: the specification requirements for the "Stop & Go" function are defined, then: a set of characteristics are selected to evaluate the energy storage systems' possibilities, the capabilities of the energy systems available now or in the short to medium term are analysed, a comparison of the needs and capabilities achieved, and finally, conclusions are drawn from the results of our analyses.

2. Preliminary part

2.1. Impact of 36 V versus 12 V — electrical needs

2.1.1. Main goals

During our study, a global electrical network analysis was performed during the programme, in order to evaluate the advantages of rising the voltage to 36 instead of the regular 12 V. It was shown that a 36 V battery has to be used for volume reasons, to fit under the car hood in reasonable conditions: more particularly, it should reduce the cost of the electronic systems used in the vehicle. This voltage should lead to currents comparable to the present situation, leaving cables on-board vehicles unchanged while there is roughly a threefold increase in the available power (*and consequently a threefold decrease in the cell capacity for the same quantity of energy stored*).

2.1.2. Functions identified

In order to adapt the battery closely to its use in a vehicle where the "Stop & Go" function should be used, several car functions were identified: starting, booster and stop. Each of these functions has been defined in terms of power and duration, and the energy involved was then estimated. Considering the fact that the starting and booster functions need something like 7 kW for periods of a few tenths of a second to a few seconds, this means total energies of about 1 and 5 W h per cycle, respectively. The two "stop phases" need 0.5–1.5 kW for something like a minute, which means a total energy of 10 and 25 W h per cycle, respectively. The two "Stop" functions identified differ mainly by the use of air-conditioning. These figures are listed in Table 1.

Table 1
Functions identified and electrical needs

Function	Characteristics	Observations
Starting	36 V–7 kW–0.3 s	1 W h/cycle Power battery
Booster	36 V–7 kW–2 s	5 W h/cycle Power and cycling battery
Stop (*low level*)	36 V–0.5 kW–1 min	10 W h/cycle Cycling battery
Stop (*high level*)	36 V–1.5 kW–1 min	25 W h/cycle Cycling battery

2.2. Energy storage characteristics considered for evaluation

In our comparison study, we decided to identify the batteries which could be considered as potential batteries for the "Stop & Go" application. Since this is "Start & Stop" driving which is being considered, the battery system for this type of application needs to be able to supply high powers and so, we focused our attention on aqueous electrolyte batteries: lead-acid, nickel–cadmium, nickel–metal hydride but also, on a few non-aqueous electrolyte batteries such as lithium-ion and tentatively lithium polymer batteries. As super capacitors are also being studied to provide high specific powers, carbon–carbon super capacitors have also been included. For immediate use reasons, the batteries considered are operating at room temperature, except the polymer battery which is operating at a temperature of 80–100°C. Concerning lead-acid batteries, we considered the different types which are the standard cells, wound cells, semi-bipolar and bipolar designs, though the last two are at the laboratory level.

In order to evaluate these batteries for the "Stop & Go" application, and in relation with RENAULT & VALEO in France, critical characteristics were selected for the evaluation of these batteries.

These typical characteristics are summarised in Table 2. Specific peak powers were determined for room temperature as well as for -20°C while specific energies were determined at a low rate of discharge — 20 h discharge rate. It must be noticed that specific energies determined at -20°C are calculated from the energies recovered at this low rate.

3. Energy storage systems

3.1. Aqueous electrolyte batteries

These batteries have several advantages compared to the non-aqueous battery technologies; they usually have a high ionic conductivity electrolyte — low cost materials as well as low cost manufacturing processes. The particular characteristic of high ionic conductivity gives these systems potentially high specific powers, difficult to reach at low cost in the other technologies (*i.e. non-aqueous*). However, these low costs may be balanced by moderate performances in terms of specific energy. Presently, available large batteries (*typically 10–100 A h batteries*), such as lead-acid batteries can reach 35–50 W h/kg, nickel–cadmium 40–55 W h/kg and nickel–metal hydride 55–70 W h/kg: their volumetric energies are, respectively, approximately 70–100, 80–100 and 130–180 W h/dm^3, making the nickel–metal hydride potentially interesting for transport applications, for space availability reasons inside vehicles.

Table 2
Characteristics selected for the "Stop & Go" battery evaluation

Room temperature characteristics (+23°C and 100% SOC — end voltage of 21 V)	
Specific power (W/kg)	At 0.3 s
Specific energy (W h/kg)	C20 h
Volumetric power (W/dm^3)	At 0.3 s
Volumetric energy (W h/dm^3)	C20 h
Low temperature discharge (−20°C and 100% SOC — end voltage of 21 V)	
Specific power (W/kg)	At 2 s
Specific energy (recovered at this rate) (W h/kg)	C20 h
Volumetric power (W/dm^3)	At 2 s
Volumetric energy (recovered at this rate) (W h/dm^3)	C20 h
Charge acceptance	
Ranked: high, medium and low	At 25°C
Ranked: high, medium and low	At 0°C
Self discharge (100–50% SOC)	
Months (except if specified otherwise)	At 23°C
Life span	
Number of cycles in the application	At 23°C
Electrical (years)	At 23°C
Mechanical (years)	At 23°C
Thermal (years)	At 50–60°C
General safety aspects ((−): no; (=): medium; (+): yes)	
Risks at chocks	At 23°C
Overcharge ability	
Deep discharge ability	
Fire propagation risk	
Others	
Possibility of SOC control (excellent, good, medium, difficult, impossible)	
Cost in EURO per kilogram for a production volume of	100,000 per year
Maintenance (with or without)	
Recycling possibility (ranked 0-low to 5-high)	
Technological state (R, R&D, D, P)	

3.1.1. Lead-acid batteries

A lot of data is available about this technology: characteristics and performances in various conditions. These batteries have the dramatic advantage of being very inexpensive in the standard technology and not really expensive in more elaborated designs. For original equipment (O.E.), starter batteries have costs of 5–7 EURO per kilowatt and of 65–85 EURO per kW h at RT, depending on the customer specifications. For newer technologies such as semi-bipolar and bipolar, these costs are approximately doubled, due a more complex design to manufacture.

For fast discharge at low temperatures (−18°C), lead-acid batteries show specific powers of 300–500 W/kg, say 500–1000 W/dm^3; in these conditions however, the specific energy at these high rates of discharge is reduced to a few W h/kg compared to the discharge at a C/20 rate, *which is the case for most of the electrochemical sources tested in these particular conditions.*

If lead-acid batteries have been at the production level for years, basic research is still being done to improve their characteristics such as the positive active material efficiency, the alloy composition, but also to design a better internal structure and get much improved characteristics: wound cells, semi-bipolar structure or true bipolar structure, which should hopefully boost specific energies to about 45–55 W h/kg and the specific power increased of about 20%, particularly for the wound cells. However, difficulties arise from such elaborated structures more particularly when considering semi-bipolar and true bipolar structures, and work is still necessary to obtain operational batteries of such types.

3.1.2. Nickel–metal hydride batteries

These batteries have been designed and studied during the last two decades more or less. Their functioning is similar to nickel–cadmium batteries, to which they are often compared since the cell voltage is the same and only the negative electrode is different (*metal hydride instead of cadmium*). These batteries have little or no memory effect, a higher specific and volumetric energy, and possibly a comparable specific power to nickel–cadmium batteries, however, this last point turned out not to be completely true. The use of metal hydrides is due to their ability to store hydrogen reversibly inside their structures, and this process of hydrogen diffusion inside a metal is significantly slower when temperature is reduced, particularly under 0°C.

In order to get an important cycle life out of these batteries, more sensitive to charging conditions than nickel–cadmium batteries, it is necessary to control their charging efficiently. In terms of storage, the behaviour of nickel–metal hydride batteries is very similar to nickel–cadmium batteries and their self-discharge turns out to be fairly high; after 30 days at 45°C, self discharge can reach about 50% of the initial capacity.

Finally, the key advantage of this technology is its volumetric energy which can reach values of 180–200 W h/dm^3 at low rates of discharge, values higher to what is obtained with high power lithium batteries such as the lithium-ion technology. Their specific energy is, however, higher than with NiCads and lead-acid batteries with 55–70 W h/kg.[1,2]

Electrical tests were performed on nickel–metal hydride cells in order to grasp the potential performance of batteries using this type of chemistry for the "Stop & Go" application. Due to the high ionic conductivity of the alkaline aqueous electrolyte, very fast discharge was possible: full capacity discharges in less than 2 min were possible at room temperature, reaching specific powers well above 500 W/kg: during test discharges at 7 C rates, specific powers of 350 W/kg were reached with a limited loss in specific energy (about 20%) (Fig. 1).

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[1] Development of advanced nickel-metal hydride batteries for electric and hybrid vehicles, JPS 80 (1999) 157.

[2] Handbook of Batteries, 2nd Edition, David Linden, 1995, § 33.27 and 33.28.

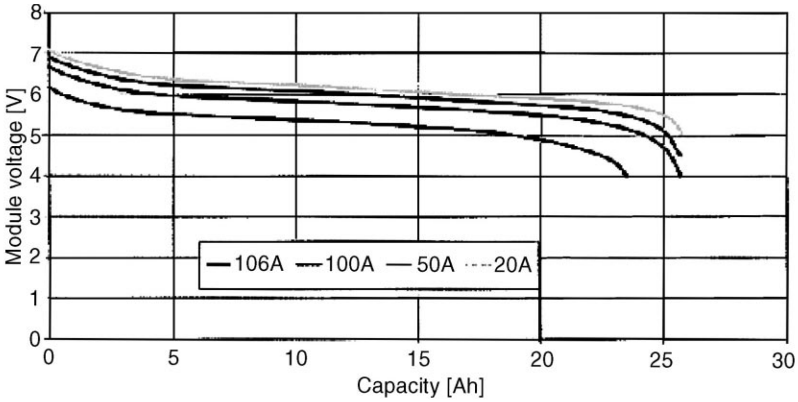

Fig. 1. Discharge curves of Ni–MH 25 A h capacity cells at various rates of discharge.

Like most of the electrochemical power sources, nickel–metal hydride batteries can achieve a large number of cycles if they are cycled with a shallow depth of discharge, meaning that 200,000 cycles can be achieved for the application.

Regarding the self discharge, like nickel–cadmium batteries, nickel–metal hydride cells can have large self discharge when the temperature is high, say, slightly more than 1% average per day at +45°C for the first month, however, at room temperature, it is lower than 0.5% per day average for the same period (Fig. 2).

The performances obtained so far show that batteries of 12–15 kg should meet the requirements for the ‘‘Stop & Go’’ functions identified.

3.1.3. Nickel–cadmium batteries

Though this technology should be out of service before 2010 (*cadmium regulation in Europe*), it has been considered as a reference. As for lead-acid batteries, a lot of data is also available about this type of batteries which has been manufactured for years for various applications such as: starter batteries for aircraft, propulsion batteries for electric vehicles as well as others. These batteries are capable of very high specific powers such as 700–1100 W/kg at room temperature, depending on the design used. Specific energies of about 40–55 W h/kg can be obtained in regular conditions (*say medium to low rates*) and very long shelf life can be obtained if properly maintained.

These batteries are able to sustain rough conditions such as high discharge rates, over-discharge, over-charge, etc. Weak points compared to lead-acid are: a decrease in performance above 40–45°C, memory effects, a higher self-discharge and higher costs (*5–10 times in terms of equivalent energy and about five times for equivalent power*). Volumetric energies are similar to what is reached with lead-acid batteries, say about 100 W h/dm^3, and low temperature operation is roughly better than lead-acid.

3.2. Organic electrolyte batteries

These batteries have several advantages over the aqueous batteries in so far as their specific energy is usually much higher (*2–3 times*) when used at medium to low rates. However, when one wants to use these batteries at higher rates, the internal structure to be used must be modified to drain high currents without too much loss through the internal resistance of the battery. In doing so, the electrode surfaces must be increased significantly, meaning more collector weight and less active material, and the specific energy of the battery is consequently reduced by these changes.

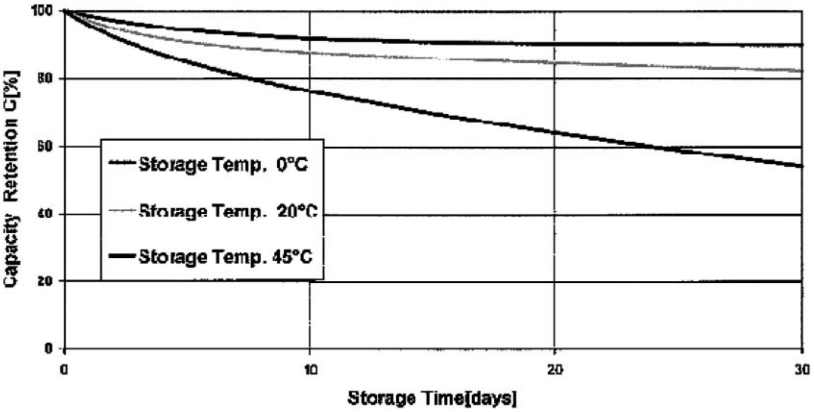

Fig. 2. Self-discharge curves of Ni–MH cells at various temperatures.

In this evaluation of non-aqueous batteries, we have only considered lithium batteries: however, it must be stressed that their manufacturing necessitates large investments (*dry rooms*) and safety aspects are key issues in terms of manufacturing, due to the large quantities of reactive materials handled.

3.2.1. Lithium-ion batteries

Lithium rechargeable cells had been studied for years and no real possibility of application demonstrated until 1990 when SONY commercialised its lithium-ion rechargeable battery (*AA size*). The key characteristic which made this possible is, instead of using metallic lithium for the negative electrode, to use lithium intercalated in a carbon material. The outcome of this, was that a large number of cycles is achievable: more than one thousand in good conditions, instead of a few hundred with a lot of difficulties. As this is a 4 V per cell chemistry, it was interesting to test it for high power applications: actually many studies have been conducted throughout the world toward that direction: military applications; EVs, etc.

These batteries can reach specific energies of about 120 W h/kg when designed for high energy applications (*meaning low power*), while designed for high or very high rates of discharge their specific energy can be as low as 60–80 W h/kg.[3]

These batteries have been studied intensively for about 10 years now, after SONY commercialised a lithium-ion battery for portable applications (*AA or R6 size*). The idea of using a particular carbon to intercalate lithium during the anodic process of cycling turned out to solve lithium cyclability, at least for practical applications, but at the expense of a slight voltage drop. SAFT has commercialised prismatic lithium-ion batteries for portable applications and is heavily involved in R&D for the application of such a battery type to electric and hybrid propulsion.

However, a delicate point concerning this system is that lithium cells need to be controlled in voltage during charge as well as during discharge in order to maintain the materials' structure and make sure of a long cycle life for the battery.

Concerning the specific power, SAFT is developing a particular technology where the specific power is increased at the expense of the specific energy. Specific powers of more than 1 kW/kg have been claimed instead of a few hundred, and specific energies of these modified cells are of 60–70 W h/kg[3] in that particular case.

Due to the lower ionic conductivity of the organic electrolyte, self discharge of such systems is lower than those observed in aqueous electrolyte batteries: however, when considering high power batteries, electrode surfaces have been extended to compensate for the low power per unit area of these chemistries, increasing at the same time self discharge which, however, remains lower than for alkaline batteries.

Prototype cells were electrically tested in order to evaluate the technology ability to sustain high specific powers. Though in organic electrolytes, conductivity is lower than in aqueous electrolytes, technological development can make it possible to develop high power batteries (*i.e. increasing the electrodes surface*). On the other hand, if pulsed power is used, as is the case for the high power required in the "Stop & Go" function, lithium-ion systems can meet the specifications (Fig. 3).

Pulsed power discharge rates of 7 C were used for testing: this rate was applied 5 s every minute to characterise the lithium-ion technology. We can see in Fig. 4 that the operational voltage stabilises at 3.1 V at the end of the pulses, indicating that operation at these high rates is within the system capabilities.

Tests were also performed to evaluate the potential difficulties which might arise from short-circuiting such cells. The rate used for this particular testing was a 10 C rate and the results are reported in Fig. 5.

During the complete discharge of the cell capacity, temperature rises from room temperature (RT) to about 130°C without any dangerous behaviour (*no container leak, burst or fire*).

3.2.2. Lithium–polymer batteries

This terminology is usually used for lithium batteries having a solid polymer electrolyte (*without any solvent*) including ionic species dissolved in it for the ionic exchanges between both electrodes. However, at room temperature the internal resistance is such that this type of system hardly has any application (*extremely low specific power presently*).

Research studies on lithium polymer batteries have been performed for now more than 25 years, and practical applications have not yet been really possible. Actually, the high internal resistance of these systems precludes "a priori" power applications due to the low specific power reached (30–50 W/kg). Moreover, beside the low specific power, the operational temperature being of 80–100°C, the application to the "Stop & Go" function in electric vehicles seems outside of the present possibility due to the thermal management to be added which reduces again specific and more particularly volumetric energies. Low temperature of operation (−20 or −30°C) is out of question, for specific power reasons, except if a heating device is added to overcome this difficulty, at the expense of the available energy densities.

Laboratories developing these lithium–polymer batteries usually operate them at a higher temperature which can be in the range of 80–100°C. The specific energy you get for such batteries at rates in the range of C/10 to C/5 is roughly equivalent to the temperature in degrees Celsius it is discharged.

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[3] SAFT lithium-ion energy and power storage technology, JPS 80 (1999) 180–189.

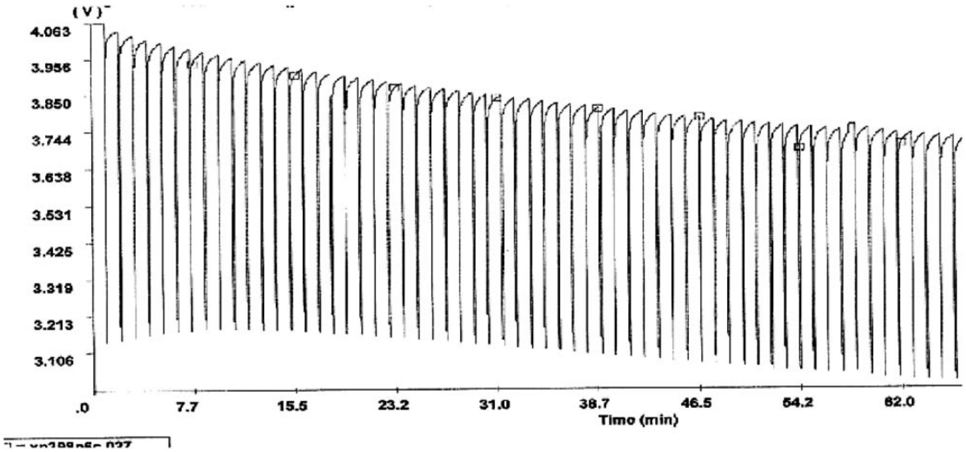

Fig. 3. Pulsed power discharge of a lithium-ion cell (7 C for 5 s every minute).

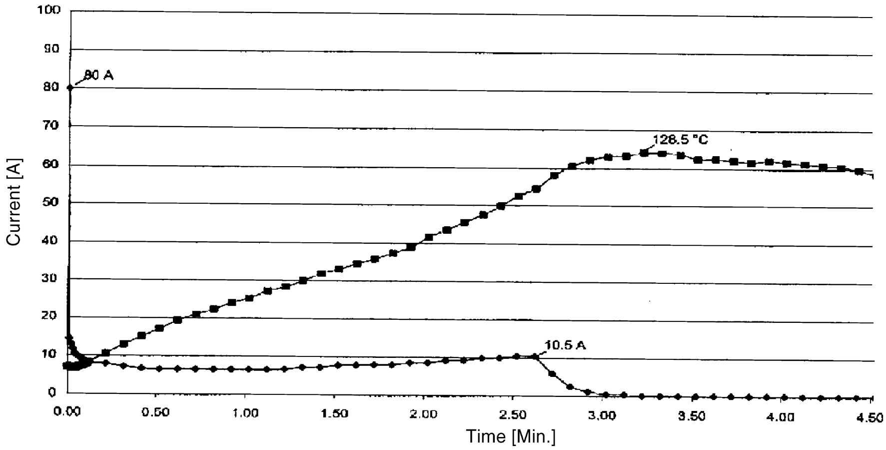

Fig. 4. Cell short-circuit (10 C rate).

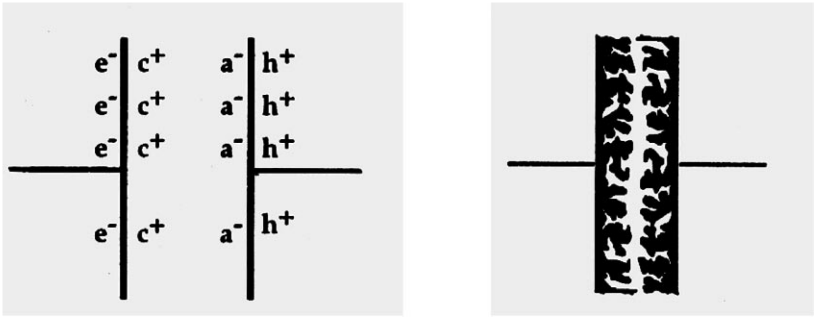

Fig. 5. Super capacitor principle.

Moreover, to get the highest specific and volumetric energy, it is necessary to discharge the cells at rates between 5 and 10 h, meaning very low specific powers at room temperature, of less than 50 W/kg. Even at C rates and 100°C, the specific power cannot be much over 100 W/kg to maintain some specific energy. Additionally, in order to keep the battery at 80–100°C, thermal insulation will have to be added, decreasing the specific and volumetric energy of the complete battery.[4]

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[4] Driving towards a viable future for EVs and HVs: US Department of Energy (DOE) storage R&D programs (1996).

3.2.3. Super capacitors

Contrary to batteries, this type of power source cannot usually be considered for long discharge times practically (*not more than a few seconds*). It is not yet completely adequate for the first starting, and looks very promising for the "Stop & Go" application where very short times are considered (*fractions of a second to a few seconds*). Specific energies can be of a few tenths of a W h/kg for aqueous carbon–carbon super capacitors to a few W h/kg when using carbon–carbon electrodes in an organic electrolytes.

The major advantage of such power devices is their specific power which can easily reach 300–500 W per kilogram in aqueous media and more than 1 kW per kilogram for the organic electrolyte version, while their cycle life is potentially much larger than the cycle lives obtained with batteries of any kind.

Though we cannot consider this device as an energy source, it is however a power source able to supply higher power densities than batteries; these can be of well over 1 kW/kg and 1 kW/dm^3. However, one can evaluate that practical powers obtained will remain below 2 or 3 kW/kg if discharge pulses for the application are a few tenths of a second or more. In these systems, the key issue to get higher practical specific powers is to decrease the global internal resistance of the cell; and the only possibility using the present technology is to manufacture thinner electrodes with larger surfaces, which will ultimately add weight.

In terms of cycling this type of device is able, theoretically at least, to reach very large numbers, even for complete discharges. This property is due to the fact that the phenomenon induced in the cell when charged is only a surface effect between two different media: electrolyte and electrode, where ions and electrons, respectively, are accumulated without modifying any species.

At EXIDE-CEAC we are doing research on organic carbon–carbon super capacitors and have reached a maximum specific power of 1500 W/kg and a specific energy of a little less than 2 W h/kg. We have also verified the very good cycling ability of such carbon–carbon devices and reached close to 10,000 cycles without characteristics modification.

Regarding the low temperature operation of these systems, it is similar to what is obtained with lithium rechargeable cells since the electrolytes are closely related. Actually, a decrease of 30–40% in terms of specific power was measured.

The drawback of the high powers obtained with these super capacitors is that self discharge is rather high: about 50% capacity decrease within 15 days (Fig. 6).

Fig. 6. 12 V super capacitor.

4. Energy storage systems evaluation and discussion

For the "Stop & Go" function, no new technology will be available at first, due to the delay in the availability of this function in automobiles. Additionally, no booster action can be considered presently since it would involve too much battery weight. These facts were considered in our analysis of the "Stop & Go" function.

Taking into consideration the data available in-house concerning the different energy storage systems considered, as well as the data available in the scientific literature, we assembled these in Table 3 to present an overview and compare the energy systems ability to meet the requirements defined. In Fig. 7, a Ragone plot has been drawn to show the characteristics of the different technologies considered in terms of specific power versus specific energy.

Additionally, considering the *energy to be recovered on braking*, it was shown that this technology, which adds cost to the system, should not be applied to small vehicles (*lower segment*) where the energy to be recovered is limited.

4.1. Discharge at cold temperatures (−20°C)

At this temperature with the type of functions considered, there is no important difference between the various systems considered in terms of specific energy: 25–45 W h/kg, the highest values being reached with bipolar lead-acid, nickel–metal hydride as well as lithium-ion batteries. However, volumetric energy is best with the nickel–metal hydride battery and reaches about 110 W h/dm^3 instead of roughly 50 W h/dm^3 for the others.

In terms of specific power, it appears that super capacitors should be the only system able to reach 1 kW/kg at this low temperature, while the others have specific powers in the range of 300 to 500 W/kg.

4.2. Charge acceptance of batteries (0 or 25°C)

For each category of battery this ability is good, except for lead-acid where it should be considered as medium at low temperature (0°C), the same being true for nickel–metal hydride batteries due to the negative electrode, when temperature goes down to −20°C.

Table 3

36 V power battery (42 V)[a]	Lead-acid battery				Ni–Cd	Ni–MH	Lithium batteries		Super CAPA C/C
	Thin flat plates (dual)	Classical flat plates	Wound and leakproof	Bipolar[b]	Aircraft Ni–Cd battery	AB2/AB5	Li-ion power	Lithium POE	Organic electrol.
Cold discharge (100% SOC)									
Specific power at −20°C (W/kg)	370	270	380	500	445	150	450	Operates at high temperature $T = 80–100°C$	1200
Specific energy at −20°C and C/20 rate (W h/kg)	25	30	30	35	35	50	30		2–3
Volume power 2 s at −20°C (W/l)	680	500	700	1000	979	350	900		1500
Volume energy at −20°C and C/20 rate (W h/l)	45	55	55	65	77	115	50		2.5 à 3.5
Operational at −30°C	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Charge acceptance									
At 0°C	Medium	Medium	Medium	Medium	Good	Medium	Good	Bad	Good
At 25°C	Good	Good	Good	Good	Good	Good	Good	Bad	Good
Room temperature operation +23°C ± 2°C									
Specific power 0.3 s (W/kg)	550	400	550	700	1000	>400	1000	50	2000
Specific energy 20 h (W h/kg)	35–40	45	40145	50–55	36	>55	70	150	2–3
Volume power 0.3 s (W/l)	980	760	1000	1300	2200	>1000	2000	65	2200
Volume energy C20 h (W h/l)	65–75	85	75185	901100	792	>125	110	200	2.5–3.5
Self-discharge 100–50% SOC									
RT = 23°C ± 2°C in months	15	15	15	15	12	12	20	No	15 days
Cyclability	200000 (2)	200000 (2)	250000 (2)	200000 (2)	>200000	>200000	>200000	>10000	>200000
Life span (in years)	4	4	4	4	>10	>5	>5	>2	>5
Mechanical durability (vibrations)	4	4	4+	4	4	4	4		4
Thermal durability (50–60°C)	OK	OK	OK	OK	No (3)	No (3)	OK	OK	OK
Safety during use									
Risks at shocks (0 = no à 5 = high)	−	−	−	−	=	=	+	+	=
Overcharge sustainability (0 = no, 5 = good)	+	+	+	+	+	−	−	−	=
Overdischarge sustainability (0 = no, 5 = good)	+	+	+	+	+	+	−	−	+
Fire extension risk (0 = no à 5 = high)	−	−	−	−	=	=	+	+	=
Others									
Possibility of charge control SOC	Medium	Medium	Medium	Medium	Difficult	Difficult	Good	Good	Excellent
Cost in EURO per kilogram (for 100,000/year)	3 E	2.3 E	4–6 E	6–8 E	25–60 E	40–60 E	40–80 E	50–100 E	50–100 E
Maintenance (with or without)	Without	Without	Without	Without	With	Without	Without	Without	Without
Recycling possibility (0 = low, 5 = good	5	5	5	5	3	3	2	2	4
Technological state	Prod.	Prod.	Development/prod.	Research	Prod.	Development/prod.	Research and development	Research	Research and development

[a] 7 kW-2 s at −20°C 100% SOC Umin 21 V; 30,000 classical startings; 7 kW-0.3 s at +20°C 150,000 cycle.

[b] Target values: (1) deep discharge and long overcharge prohibited; necessitates a cell management unit for charge and/or discharge periods; (2) battery sized according to power; hot starting is equivalent to 0.15% DOD, say a life expected of 200,000 cycles; (3) bad operation when hot; thermal management unit necessary.

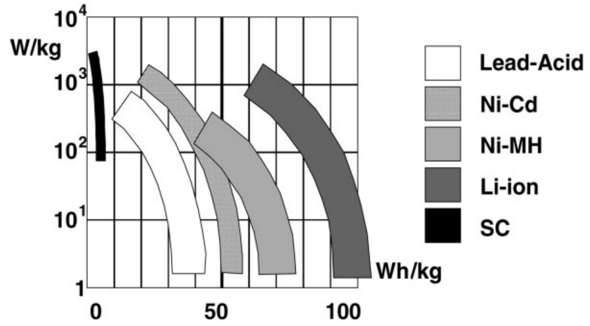

Fig. 7. Ragone plot of the specific power vs. specific energy for the different technologies considered.

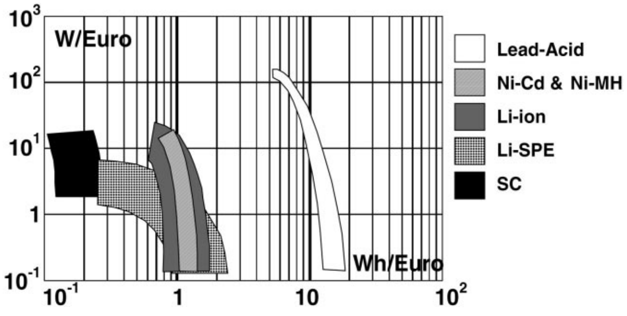

Fig. 8. Ragone plot of the watts per Euro vs. the watt-hours per Euro for the different technologies considered.

4.3. Discharge at ambient temperatures (+23°C)

At this temperature, organic electrolyte batteries have larger specific energies of about 65–80 W h/kg while lead-acid batteries remain in the 35–50 W h/kg range and the alkaline systems at about 40–65 W h/kg.

Regarding specific power, organic electrolyte super capacitors emerge with values of more about 2 kW/kg while NiCads can reach 1 kW/kg: the others are in the range of 400 to 700 W/kg. Actually, at this temperature, any electrochemical system considered, except lithium–polymer, has an adequate specific power for the application.

4.4. Batteries self-discharge (23°C — from 100–50% SOC)

Comparing self-discharge of the different energy storage systems considered in the study shows that this characteristic is roughly related to the specific power of the systems. Those having the highest specific power: super capacitors, have the highest self-discharge of roughly 8 days for aqueous electrolyte and roughly 15 days for organic electrolyte ones, less conductive than aqueous electrolytes. Then NiCads with 12 months, lead-acid with 15 months and finally lithium systems with 20 months.

4.5. Cycle life and life span

Cyclability can be fulfilled with every system proposed in so far as we are considering very shallow depths of discharge which make the 200,000 cycle target rather easy to reach.

On the other hand, we were not able to get the information about the life span of each product, particularly on lithium polymer systems, since only lead-acid and NiCads have been produced and field tested in large quantities.

4.6. Safety aspects

Concerning these aspects, one can say that classical systems (*with lower specific energies*) as well as low energy content systems such as super capacitors have a better safety behaviour and are more easily controlled in case of abuse conditions. Regarding the high energy systems like lithium batteries, they need much more attention and control to reach a usable stage, and so they have higher risks.

4.7. Prices

Though the evaluation of price needs additional details, a rough evaluation of the power price in EURO per kilowatt using the values entered in Table 3 shows that whatever the operational conditions, lead-acid batteries are at least five times less expensive making this energy storage system, the system of choice for the ‘‘Stop & Go’’ function in cars.

We plotted, in a similar way to the Ragone plot for specific power versus specific energy, watts per Euro versus watt-hours per Euro in Fig. 8 and got an interesting overview of the various technologies presently possible in terms of costs, where the function price has been considered.

5. Lead-acid battery: the battery of choice?

When considering battery selection for an application, the use of a lead-acid battery is almost dictated where cost is of primary importance, which is the case for car manufacturers, more particularly for the low segments vehicles. Actually,

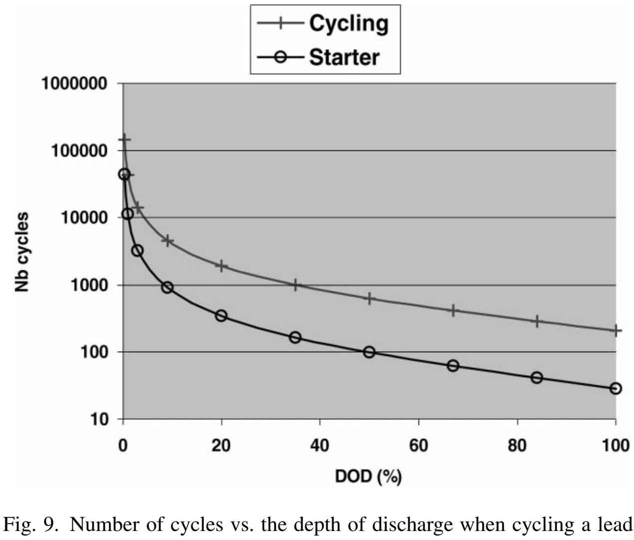

Fig. 9. Number of cycles vs. the depth of discharge when cycling a lead-acid battery.

Table 4
Possibilities identified

Scenarios	Starter	Starter and booster	Starter, booster and stop	Starter, booster, stop and air-conditioned
Battery type	Power	Power and cycling	Cycling	Cycling
W/kg at +25°C (2/3 at −18°C)	600	420	360	360
dm^3	12	14	16	16
kg	20–25	25–30	35–40	35–40
Life span (years)	>4	3–4	3–4	2–3

Fig. 10. Photograph of a 36 V lead-acid battery prototype.

customers are not prepared to pay more expensive products having quasi identical characteristics, and cars are market-driven rather than technologically-driven products.

Operational life for batteries is quite an issue and, for lead-acid batteries, the available data in-house was used to draw a chart where the number of cycles obtained is plotted versus the depth of discharge (dod) applied to the battery.

As an example, a few percents dod allow for one thousand cycles to more than a hundred thousands, depending on the technology considered as well as on the dod used in the application. An advantage of one decade to the cycling type lead-acid battery can be observed on Fig. 9.

At EXIDE/CEAC different lead-acid concepts and battery designs have been studied and developed, which can easily be adapted at a lower cost than presently proposed new technologies: Figs. 10 and 11.

As different possibilities exist concerning the structure of the application, and after having defined the functions needs in Table 2, four different possibilities were defined for light weight vehicles: starter only — starter and booster–starter, booster and stop and finally starter, booster, stop and air-conditioned vehicle. In these different cases, the electrical results obtained with lead-acid batteries have been calculated and reported in Table 4.

6. Conclusions

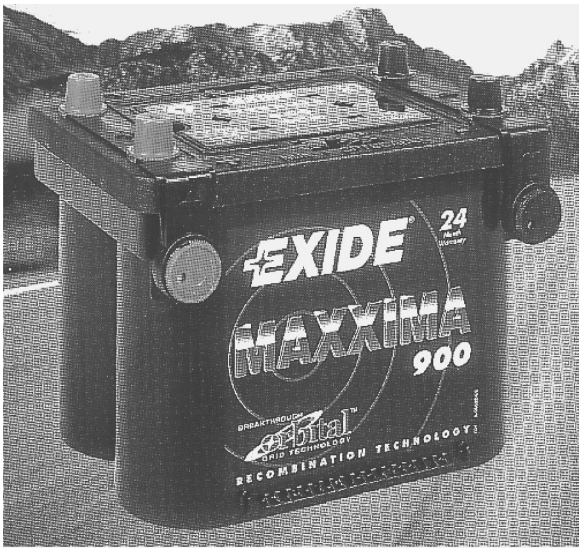

Fig. 11. Photograph of a high power 12 V wound lead-acid battery.

Due to the work performed at EXIDE-CEAC during the present programme, if the starter–alternator function is being used in future vehicles, it appears that lead-acid batteries will still have a dominant role in this type of application for cost-efficiency reasons, by far the lowest of every battery presently available or in the development stage, either for the price itself or the function cost.

This is even more particularly true for the low segments cars. Indeed, the starter function is 20 times less expensive than new technologies such as nickel–metal hydride, and others.

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