Automotive battery energy density — past, present and future

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Abstract

Energy and power densities of automotive batteries at engine starting rates have doubled over the past twenty years. Most recent improvements can be credited to the use of both very thin plates with optimized grid design and low-resistance polyethylene separators with a thin backweb and a reduced rib height. Opportunities for further improvements using the same design approach and similar processing techniques are limited. The effect of some recent innovative developments on weight reduction and performance improvement are reviewed, together with possible changes to the electrical system of vehicles.

Introduction

The versatility and intrinsic capability of the lead/acid battery is illustrated by the substantial improvements in the performance of the automotive version. Whilst the energy and power capability have increased progressively, weight, volume and cost have continued to decrease. Energy and power densities at engine starting rates have more than doubled over the past twenty years, whilst many new features have been introduced, such as maintenance free operation, dual terminals, multiple fitments, etc.

In recent years, these improvements can be credited mainly to the introduction of new manufacturing methods to produce and use ultra-thin plates with optimized grid design, envelope and low-resistance separators, and shorter intercell connections. Without the earlier research, which provided the understanding and materials for corrosion- and creep-resistance alloys and thin flesh microporous separators [1–5], implementation of these new techniques would not have been possible.

This review summarizes recent improvements and examines the effects of changes in separator and grid design. It raises the question as to whether the limit of product improvement is being reached with existing designs and manufacturing methods. The effect of some recent innovative developments are also considered. Finally, the impact of higher voltage electrical systems in vehicles on battery design is examined.

Present performance levels

The SAE ratings of cold-cranking current (the current supplied for 30 s at −18 °C whilst sustaining a voltage of 7.2 V) and reserve capacity (the

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duration to 10.5 V when discharged at 25 A at 25 °C) are the accepted standards. The ratings are widely used benchmarks when the performances of automotive batteries are compared. Due to the voltage limitations, both performances are influenced by ohmic factors such as the resistance of the electrolyte within the pores of the separator, the resistance of the grids, top-lead conducting paths, active material and solid/solid and solid/liquid interfaces. Clearly these factors exert a major effect on the cold-cranking current (CCA), whilst the reserve capacity may also be limited by blocking of the pores within the active material. Acid depletion then causes rapid polarization.

Two major design changes in recent years have contributed to the improvement in energy and power density. These are the use of increasingly thinner grids with a lattice network designed to optimize conductivity, and the progressive introduction of polyethylene separators with very thin backweb and enveloped to give edge protection and to allow the plate group to be positioned on the base of the container. Both have reduced the internal resistance and improved the availability of acid to the active material. These advances have given rise to a substantial improvement in both cranking performance and reserve capacity.

Production from strip lead sheet or by continuous casting methods has accelerated the move towards thinner grids. Thicknesses of 1 mm, or slightly less, are now common. In addition, grids can be made in a variety of designs aimed at improving conductivity and maintaining electrical performance whilst minimizing grid weight. Figure 1 illustrates the effect on conductivity of relocating the lug and orienting the grid wires in a radial network [6]. With the radial design, the resistance from the lug to over 80% of the grid surface is less than 3 mΩ, whereas more than half of the rectilinear grid has a higher resistance. The move to calcium, or very-low antimony alloys, has also improved conductivity and reduced grid resistance.

Reducing plate thickness also improves the utilization of the active material. Bode *et al.* [7] measured the sulphate levels across plates after discharging at different rates. For discharge duration of less than 1 h, the

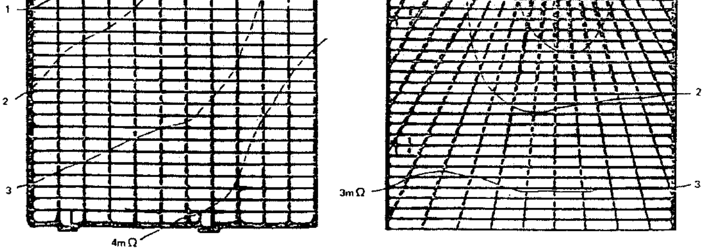

Fig. 1. Ohmic resistance maps of automotive grids [6].

sulphate concentration inside the plate was much lower than at the surface due to acid depletion. Thinner plates reduce this effect and increase the coulombic efficiency of the active material.

The second major change in recent years has been a progressive decrease in the resistance of the electrolyte between the plates. This has been achieved by using polyethylene separators with low backweb thicknesses and reduced rib height. Separators with 0.20 and 0.25 mm backweb are now common and by modifying the composition, pinhole-free material with backweb as thin as 0.125 mm can be made. The decrease in resistance as the thickness of the backweb is reduced is shown in Fig. 2. The small pore size in these separators, coupled with high puncture and tear resistance, makes this possible without the risk of shorts or dendrite growth through the very thin sections. In addition, the flexibility and ease of sealing polyethylene makes envelope formation a simple operation. Enveloping not only provides a further safeguard against internal shorts but also enables the acid reservoir to be located above the plates where it is most effective, thereby making still more efficient use of space and materials.

The improvement in energy density at cold-cranking and reserve-capacity rates of discharge as a result of the above and earlier changes is shown in Fig. 3. Based on 1989 catalogue data, the cold-cranking performance of premium products has more than doubled to 43 W h kg^{-1} in 20 years. By contrast, at the lower rate, the reserve capacity has increased by about 20% from 5.2 to 6.3 min kg^{-1}.

The influence of lower resistance on engine starting capability is demonstrated better by comparing the 5 s power output during the cold-cranking discharge (Table 1). Clearly the battery design engineer has the option of providing much superior engine start performance with weight equivalent to conventional batteries, or equivalent high-rate performance with considerably less weight.

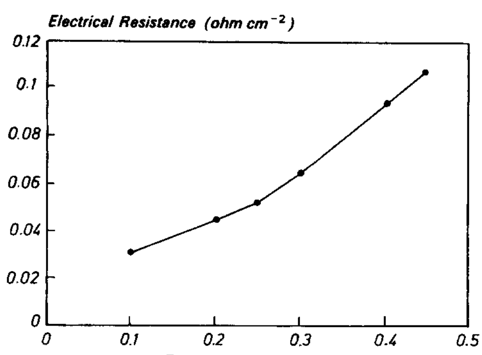

Fig. 2. Electrical resistance as a function of backweb thickness (data supplied by Cookson Entek Ltd.).

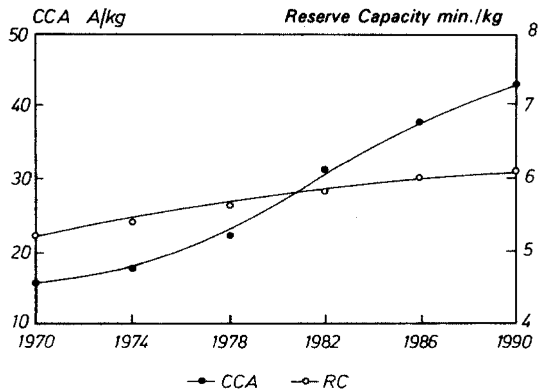

Fig. 3. Improvements in energy density (based on SAE cold-cranking and reserve-capacity tests).

TABLE 1

Power output at 5 s (at specified cranking current at −18 °C)

	Group 24 design	
	1979	1989
Weight (kg)	18.5	16.3
Battery volts (V) at 5 s at rated current	7.80	8.52
Power at 5 s (kW)	3.9	5.55
Power density at 5 s (W kg^{-1})	210	345

Future prospects

There are no indications that the changes discussed previously have significantly effected service-life. It can be assumed, therefore, that further improvements using similar design approaches depend upon the ability to make thinner sections with the necessary quality and integrity. Using modern processing and handling methods, it seems feasible to produce grids as thin as 0.75 mm and to reduce backweb thickness of polyethylene separators to 0.125 mm. This would give, at least, a further 10% increase in energy density at cranking rates whilst maintaining adequate reserve capacities. Changes in dimensions beyond these levels without affecting the integrity of the components is difficult and further improvement using conventional designs and processes is unlikely.

Consequently, evolutionary improvement of existing designs will continue for some years. There is every indication, however, that car manufacturers will continue to require lighter batteries as long as performance and reliability are maintained. To meet this demand, new approaches to design or processing may be necessary. At the same time, changes in the electrical system, aimed at reducing the overall weight and improving fuel efficiency, could alter specifications and power requirements. Recent developments that could further improve energy and power density are considered below and possible changes in vehicle electrical systems are examined.

Valve-regulated (sealed) automotive batteries

Because of performance limitations and cost, valve-regulated (sealed) automotive batteries have not been used for original equipment and have found only niche applications in the replacement market. Until fitted as initial equipment, they are likely to have only limited appeal in spite of beneficial features such as safety, convenience of fitting, and improved starting power. Early production problems have been overcome and manufacturing cost is decreasing. The glass-fibre separators conform to the plate surface under compression and have a very low resistance (see Fig. 4) due to the low tortuosity of the pores and high porosity of the material.

Early production versions of these batteries (about 1980) had much higher power capability than other premium designs of the same period [8]. With the present-day plate designs, it is estimated that energy densities of 46 to 48 A kg^{-1} at engine starting rates are achievable. One of the early drawbacks to the absorbed electrolyte design was the reduced low-rate performance caused by acid limitation. The trend to increasingly thinner plates associated with highly porous separators reduces this problem and similar reserve capacities to equivalent sized, flooded cells can be achieved.

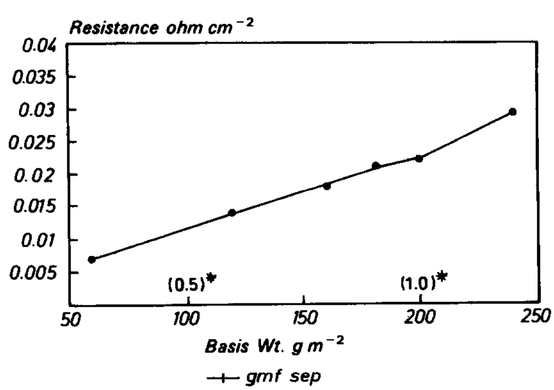

Fig. 4. Resistance of absorptive gmf separators; *separator thickness in mm (compressed).

Cal-Tec process

This process [9] takes grid making by the lead strip process a stage further by coiling the plates and keeping them apart using projections on the lug. With this technique, it is claimed that approximately one half of the grid metal can be eliminated. After pasting, the plates are ribbed — increasing the plate surface — and assembled with flat polyethylene separators of thickness 0.2 to 0.25 mm. In a further development plates can be formed on the coil ready for assembling into a dry charged product and shipping. Coils containing up to 30 wraps have been formed so far and the process is being scaled up to a commercial level [10].

Automotive batteries made by this process have energy densities of 50 A kg^{-1} at cold-cranking rates. It is claimed that the process gives a substantial reduction in manufacturing cost. Table 2 gives some design and performance details.

Electrosource process

This process [11] is a method of making grids using co-extruded lead wire, pasting with a proprietary paste, and building a low resistance, sealed recombination battery. The design consists of layers of plate frames. Each frame contains positive and negative sections linked together by the wire conductor. These represent plates in adjacent cells. By laying down frames of alternate polarity, a multicell battery can be built without top lead, apart from terminal connections and posts. Assembled with absorbent glass separators, the battery has a very low resistance and is potentially cheaper to make. The design and assembly is shown in Fig. 5.

To date, the priority of the development programme has been to produce high energy density, cycleable batteries for electric vehicles and only design exercises have been carried out on automotive applications. These studies show high A kg^{-1} values at cranking rates, as would be expected from the weight reduction coupled with a decrease in battery resistance. Values approaching 70 A kg^{-1}, together with adequate reserve capacities can be expected with suitable separator/plate ratios. Table 3 summarizes the

TABLE 2

Automotive batteries made by the Cal-Tec process

	Standard	Cal-Tec
CCA (A)	525	525
Volume (dm^3) (inc. terminals)	7.08	4.48
Weight (kg)	16.5	10.5
Energy density (A kg^{-1})	32	50

This is a Group 26 design and the Cal-Tec battery had 10 plates per cell using grids (0.62 mm at top to 0.50 mm at bottom) weighing 14 to 21 g with plate thickness of 1.6 to 1.7 mm(+) and 1.4 to 1.7 mm(−) and 0.25 mm flat polyethylene separators.

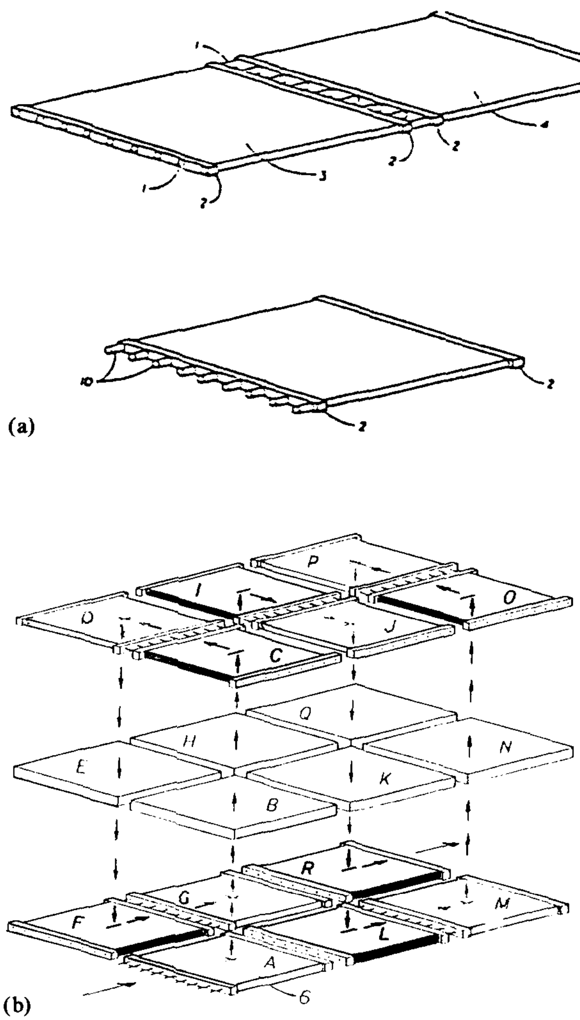

Fig. 5. Battery assembly using electrosource process: (a) pasted bi-plates, full and half; (b) 12 V (2 × 3) assembly showing current path.

TABLE 3

'Horizon' automotive batteries (projections for Group 42 (SAE) size)

Size (mm)	243(l) × 172(w) × 170(h)
Weight (kg)	14.2
CCA (A)	960
Reserve capacity (min.)	85
CCA/kg	67.5
Min./kg	6.0

expected performance of a Group 42 (SAE) battery made to this design (codenamed the 'Horizon' battery).

Bipolar designs

Recent research into lightweight bipolar lead/acid batteries [12, 13] demonstrates further the high power capability of this system. The combination of high open-circuit voltage and low electrolyte resistivity provides the possibilities of very high specific power, surpassed by few other electrochemical couples. These values can only be achieved, however, if the mass of the conductors (grids, top lead, etc.) is greatly reduced. Bipolar design is the obvious approach but studies have yielded little success in the past.

The most recent activity involved the development of a sealed 50 kW bipolar battery for defence applications using lightweight composite electrodes of conductive glass and carbon fibres embedded in a polymeric matrix. In addition, tin oxide coated glass-fibres were included in the positive active material. Battery stacks of 50 cells were assembled and these had a specific power of 1.5 kW kg^{-1} on a 100 s continuous discharge and 5 kW kg^{-1} over several thousand pulses. Accepting that this activity is far from the commercialization stage, it illustrates what might be considered as the ultimate in specific power.

Changes in vehicle electrical systems

With the emphasis on safety and reliability, automobile designers are considering ways to improve the electrical system as a whole with the battery as an integral part of this system. The increasing use of electrically-powered components will need a further increase in the size of alternators. Alternator output has doubled in the last 15 years and predictions suggest a further doubling in the next ten years [14].

This increase in electrical load makes a higher voltage system desirable. Using the existing 12 V generator, outputs up to 200 A would be required. This would increase the size, weight and cost of the wiring and result in higher ohmic losses and temperatures. Many factors need to be considered when choosing the system voltage. A dual, or triple, voltage arrangement may best satisfy all the requirements.

On safety grounds, near-term changes will most likely be limited to 24 V, with a 12 V lighting system powered from an inverter giving constant light output independent of battery voltage variations. This would ensure long bulb filament life. In the longer term, battery voltages of 36 or 48 V may be preferred, using high frequency inverters for the higher voltage applications to improve safety.

Should these changes take place, car manufacturers will continue to want low battery weights. Capacities will be reduced in proportion to the voltage increase and there will be a greater need to minimize voltage losses between cells. Such a change is likely to accelerate moves towards new battery designs with increasing interest in low-resistance systems.

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