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Advanced design of valve-regulated lead–acid battery for hybrid electric vehicles

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Abstract

A novel design of lead–acid battery has been developed for use in hybrid electric vehicles (HEVs). The battery has current take-offs at both ends of each of the positive and negative plates. This feature markedly reduces battery operating temperatures, improves battery capacity, and extends cycle-life under HEV duty. The battery also performs well under partial-state-of-charge (PSoC)/fast-charge, electric-vehicle operation. The improvements in performance are attributed to more uniform utilization of the plate active-materials. The battery, combined with an internal-combustion engine and a new type of supercapacitor, will be used to power an HEV, which is being designed and constructed by an Australian industry–government consortium. © 2000 Elsevier Science S.A. All rights reserved.

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1. Introduction

Exhaust emissions from road vehicles are a major cause of both Greenhouse-gas build-up and urban pollution. Increasing world-wide concern over these issues has resulted in the introduction of new anti-pollution legislation, which significantly restricts exhaust emissions from internal-combustion engined (ICE) vehicles. Some countries have been particularly severe in their approach and have legislated that a certain number of vehicles sold must be either low-emission (i.e., hybrid electric vehicles, HEVs) or zero-emission (i.e., electric vehicles, EVs). Clearly, the success of such strategies to improve air quality hinges on the development of vehicles, which have acceptable performance and affordable life-time costs.

Following a CSIRO initiative in late-1997, a consortium was formed to design and build a prototype HEV, the *aXcessaustralia II*. The consortium comprises CSIRO, Australian car component manufacturers, and several Australian Government organizations. The vehicle will be powered by an ICE, an advanced valve-regulated lead–acid (VRLA) battery pack, and a novel supercapacitor module.

Battery packs in HEVs are required to operate for many cycles below a full state-of-charge (SoC). They are also subjected to both high charge and discharge currents. Operating VRLA batteries under this duty has been shown [1–3] to result in the irreversible formation of lead sulfate in battery plates, especially at the bottom of the negatives. Whilst equalization (i.e., rigorous, full recharging) of the batteries retards the onset of this debilitating phenomenon, HEV manufacturers would prefer to reduce the frequency of the equalization operation so that it can be performed during vehicle servicing. This is more practical as participation of the owner is avoided and the requirement for a separate onboard or 'home-based' charging system for battery equalization is removed.

To address the problem of charge maintenance, a new design of VRLA battery has been developed by CSIRO in collaboration with Hawker Energy Products in the USA. The 12-V unit, called the 'Double-Impact™' battery, has a current take-off ('tab') at the top and bottom of each of the positive and negative plates.

This paper reports the preliminary performance of the Double-Impact™ battery in comparison with a state-of-the-art commercial VRLA battery (equivalent size, weight and

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rated capacity) under both HEV and partial-state-of-charge (PSoC)/fast-charge EV duties.

2. Battery performance

2.1. Operation under standard cycling conditions

Clearly, the Double-Impact™ battery should give similar performance under standard cycling conditions to state-of-the-art, single-tab, commercial technology. Hence, the Double-Impact™ battery and the chosen commercial unit were tested under a variety of discharge rates. The results (expressed in terms of Wh kg^{-1}), together with the relevant physical parameters of the two batteries, are shown in Table 1. The performance of both batteries varies by no more than ~10% at all rates of discharge. This confirms that the Double-Impact™ battery matches best available technology under standard cycling conditions.

2.2. Operation under simulated HEV duty

The performance of both the Double-Impact™ and the commercial VRLA battery has been evaluated under simple, simulated HEV profiles, which are known to encourage the formation of 'hard' lead sulfate [3], i.e., lead sulfate which is difficult to recharge. The schedules involve the following steps:

(i) discharge at $2C_1$ to 50% SoC,
(ii) charge at specified rate ($2C_1$ or $4C_1$) for 1 min,
(ii) rest at open-circuit for 10 s,
(iv) discharge at specified rate ($2C_1$ or $4C_1$) for 1 min,
(v) rest at open-circuit for 10 s,
(vi) repeat (ii) to (v) until the voltage decreases to 10.0 V at the end of step (iv) or increases to 15.0 V at the end of step (ii).

Table 1
Capacity of commercial and Double-Impact™ batteries at different discharge rates

Discharge current (A)	Specific energy (Wh kg^{-1})	
	Commercial[a]	Double-Impact™ [b]
21.5	25.8[c]	25.1[c]
166	17.4[d]	18.1[d]
260	12.9[d]	12.9[d]
360	11.2[d]	11.6[d]
500	10.4[d]	9.01[d]

[a] Weight = 10 kg; size = 16 × 17 × 12.5 cm.

[b] Weight = 11 kg; size = 16 × 17 × 15.0 cm. Note, the top-lead configuration has not been optimized — further refinements are expected to reduce the weight by ~1 kg.

[c] Discharge voltage limit = 1.75 V/cell.

[d] Discharge voltage limit = 1.20 V/cell.

2.2.1. $2C_1$ HEV duty

When subjected to $2C_1$ charge and discharge, the commercial and the Double-Impact™ batteries delivered 6900 and 8800 HEV cycles, respectively, before their end-of-discharge-voltages (EoDVs) dropped to 10.0 V (Fig. 1) and equalization charging was required. The greater cycle performance exhibited by the Double-Impact™ battery would represent a 25% decrease in the frequency of equalization. As mentioned above, improvements of this kind are required by HEV manufacturers so that equalization charging can be performed during routine vehicle servicing.

Reductions in equalization frequency under simulated HEV duty have also been achieved [1,2] through the addition of high levels of carbon to the negative active-material. The need for less equalization was attributed to the deposition of a thin layer of carbon over the lead-sulfate crystals which, in turn, increased the conductivity of the active material. Given these observations, it is considered likely that a combination of Double-Impact™ technology and improved negative-plate additives may provide an effective solution to the problem of reduced battery capacity under HEV duty that has been reported by several workers [1–3].

The temperature of the commercial battery, measured externally at the side of the battery case, increased gradually during operation and reached 65°C at the completion of 6900 HEV cycles (Fig. 1). Previous studies [4] have shown that the internal temperatures of batteries can be up to 20°C higher than the external temperatures under similar duty. Hence, continued operation of the above batteries (Fig. 1) would probably have resulted in thermal runaway.

By contrast, the temperature of the Double-Impact™ battery remained at 38 ± 2°C throughout its cycling period (Fig. 1). This is almost 30°C cooler than that of the commercial battery. Clearly, the Double-Impact™ battery is much less susceptible to temperature increases (and, therefore, thermal runaway) under extended HEV operation than the commercial unit. This performance characteristic is very attractive to HEV manufacturers as the cooling requirements for Double-Impact™ battery packs would be much simpler. Also, the lower operating temperatures should reduce both corrosion of the positive grids and degradation of the expander used in the negative plates. Moreover, electrolyte dry-out — a condition which can increase the internal resistance of the battery — would be minimized.

2.2.2. $4C_1$ HEV duty

The performance of the Double-Impact™ and the commercial batteries was evaluated under HEV duty with a charge and discharge rate of $4C_1$. The increase in these rates from $2C_1$ to $4C_1$ was expected to cause a considerable increase in the operating temperature of the batteries. Hence, as a precaution, a temperature probe was inserted

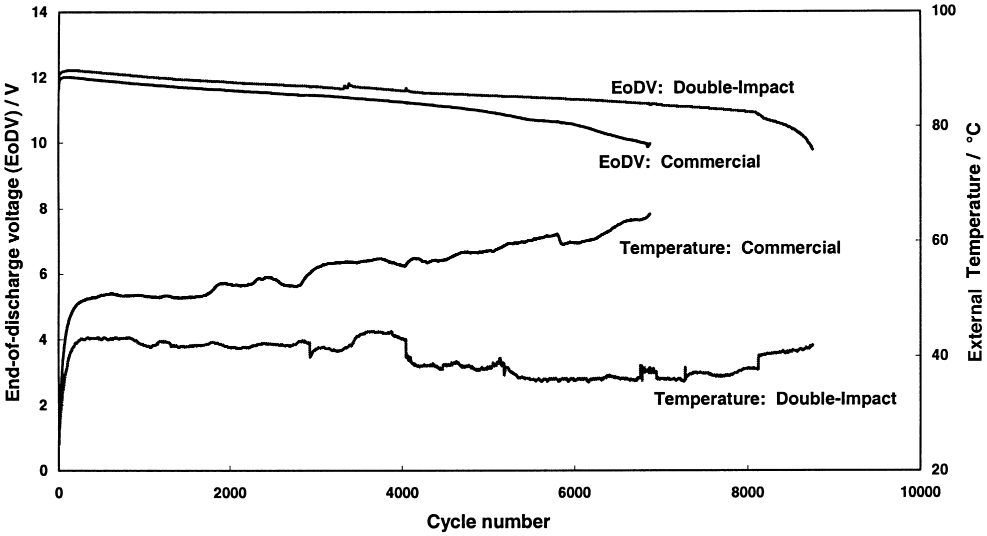

Fig. 1. Performance of Double-Impact™ and commercial batteries under simulated HEV cycling (charge, discharge rate = $2C_1$).

into each battery in the middle of the third cell (from the positive terminal) between the most central negative plate and the adjacent separator. The temperature was also monitored externally at the hottest area on the battery case. Furthermore, in the interests of safety, both batteries were removed from cycling when the external temperature reached 50°C.

After 50 cycles, the external temperature of the commercial battery reached 50°C (Fig. 2). At this stage, it was found that the internal temperature had increased to approximately 70°C. By contrast, the Double-Impact™ unit operated for 120 cycles before the same external temperature limit was reached. Hence, as with $2C_1$ HEV operation (see above), the addition of the second current take-off significantly reduces the operating temperature of the Double-Impact™ battery compared with that of traditional, single-tab designs.

2.3. Operation under PSoC / fast-charge EV duty

Fast charging has been extensively demonstrated [4–7] as an effective means for overcoming the limited range of lead–acid-powered EVs. Also, other studies [3,8] have shown that PSoC operation (e.g., repetitive cycling below a full SoC) can offer remarkable improvements in the lifetime energy available from VRLA batteries.

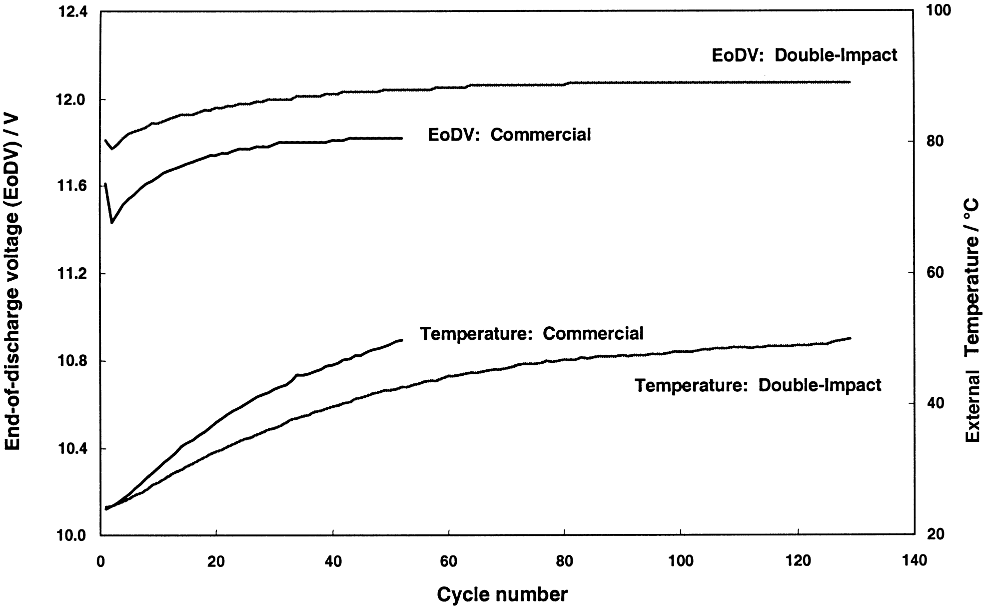

Fig. 2. Performance of Double-Impact™ and commercial batteries under simulated HEV cycling (charge, discharge rate = $4C_1$).

In response to the above observations, a research programme was initiated in 1997 between the Advanced Lead-Acid Battery Consortium, Arizona Public Service, Electric Transport Applications, CSIRO and Hawker Energy Products to establish whether the combination of fast-charge and PSoC duty can improve both the driving range of EVs and the lifetime energy of battery packs. As this type of EV operation is similar to HEV duty, i.e., fast charge (up to $6C_1$) and extended operation within a fixed SoC window, it was decided to evaluate Double-Impact™ technology under PSoC/fast-charge EV conditions. Accordingly, Double-Impact™ and commercial batteries were operated continuously under the following three regimes, which were applied sequentially.

Regime 1 — the battery is discharged from 100% to 20% SoC at the C_1 rate (based on Ah removed).

Regime 2 — the battery is charged at $6C_1$ from 20% to 80% SoC (based on Ah input). The battery is then discharged at the C_1 rate to 20% SoC (based on Ah removed). The charge–discharge operation between 20% and 80% SoC without full recharging is referred to as a 'PSoC cycle'. The PSoC process is continued for 24 PSoC cycles, or until the battery voltage at the end of discharge decreases to 11.1 V. At this point, the battery is deemed to be at 10% SoC, e.g., an initial PSoC operating window of 20 ⇔ 80% SoC has become 10 ⇔ 70% SoC. One set of 24 PSoC cycles is referred to as a 'master cycle'; it represents a vehicle driving distance of around 1000 km.

Regime 3 — (i) the battery is charged at $6C_1$ until the current falls to 5 A; (ii) the battery is then equalized with a constant current for a specified time.

It is to be noted that the PSoC/fast-charge schedule adopted here is quite severe in that the equalization period is both brief (~ 1 h) and infrequent (~ 1000 km).

The results of the test, expressed in terms of the EoDV at the completion of discharge in Regime 2, are shown in Fig. 3. The EoDV of the commercial battery initially increased in response to a rise in battery temperature, caused by the commencement of fast charging. The EoDV then decreased steadily from 11.75 to 11.45 V during the remainder of the master cycle, presumably as a result of charging inefficiencies. The EoDV recovered after equalization charging (Regime 3), but then decreased gradually to 11.45 V during the second master cycle. The EoDV after the last discharge of the third master cycle had decreased to 11.15 V, compared with 11.45 V during the first and second master cycles. This 'irreversible' degradation of the EoDV continued such that the battery voltage reached the cut-off limit of 11.10 V during the last discharge of the fourth master cycle. In all subsequent master cycles, the battery was unable to deliver 24 cycles before reaching the cut-off voltage.

By comparison, the EoDV of the Double-Impact™ battery remained at a much higher level throughout PSoC/fast-charge operation (Fig. 3). For example, the values of the EoDV during the last discharge of the first and final master cycles were 11.70 and 11.50 V, respectively, compared with 11.45 and 11.10 V for the commercial unit. Hence, the Double-Impact™ battery is more resistant to capacity loss under PSoC/fast-charge duty and, as a consequence, was able to deliver the required number of PSoC cycles throughout the testing period.

Each of the commercial and Double-Impact™ batteries used in the PSoC/fast-charge experiments was fitted with three internal thermocouples in order to measure the 'actual' operating temperature of the batteries. The probes were installed in the third cell and were positioned between the middle negative plate and adjacent separator in

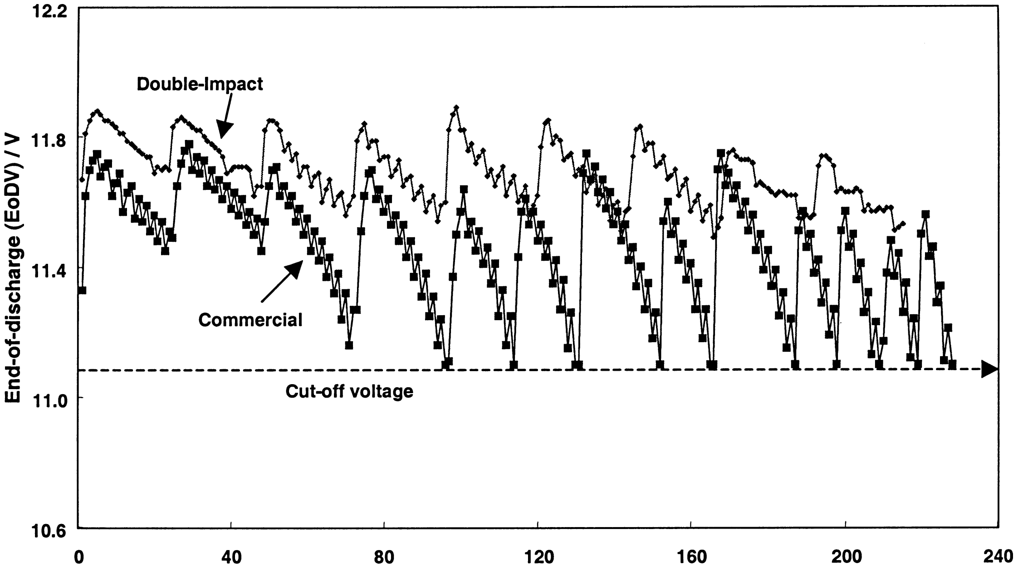

Fig. 3. Capacity performance of Double-Impact™ and commercial batteries under simulated PSoC/fast-charge EV duty ($6C_1$ charge rate).

the following positions: (i) 1 cm from the top of the cell group; (ii) middle of the cell group; (iii) 1 cm from the bottom of the cell group. The internal temperatures of both batteries at the completion of charging during the fourth master cycle are shown in Fig. 4. A temperature gradient formed quickly in the commercial battery during initial operation. After four cycles, the internal temperature reached 90°C, 75°C and 70°C at the top, middle and bottom of the battery, respectively. The extent of the rise was surprising, given that the external temperature was only 55°C at the hottest point on the outside of the battery case.

Under fast-charge conditions, the ToCV of a battery is usually compensated for increases in temperature to avoid overcharging. For a 12-V unit, this is achieved by reducing the ToCV by 24 mV for each 1°C increase in battery temperature above 25°C. For practical reasons, this calculation is usually based on the external battery temperature. In the above experiments, however, the external temperature was at least 20°C lower than the average internal temperature. Hence, it is obvious that normal practice would result in inadequate control of the battery voltage. Note, significant differences in the external and internal battery temperatures were also observed under $4C_1$ HEV duty, see Section 2.2.2, above. Clearly, the method of temperature compensation commonly used by HEV and EV operators requires urgent revision.

The internal temperature of the Double-Impact™ battery increased gradually during initial PSoC/fast-charge operation; the temperature reached approximately 65°C after 7 cycles (Fig. 4). During that time, the temperature differential from the top to the bottom of the battery did not exceed 5°C. Hence, Double-Impact™ batteries experience both a lower average battery temperature and a reduced internal-temperature differential, compared with traditional battery designs, when operated under PSoC/fast-charge conditions. This improvement in performance can be attributed directly to the dual-tab nature of battery. In traditional designs, there is a significant increase in current density (i.e., there is 'current concentration') in the region of the current take-off at the top of the battery plates during high-rate charge/discharge. As heating within batteries is related to both the square of the current and the resistance of the battery (i.e., I^2R), high and localized current densities at the top of plates can lead to large heating effects. The inclusion of a second current take-off at the bottom of the plate produces a lower and more uniform current density within the plate, and thus reduces the overall amount of heat generated. Moreover, this design assists heat dissipation, which serves to equalize temperatures throughout the battery.

It has been demonstrated [1–4] that the operation of VRLA batteries under PSoC duty can cause the build up of 'hard' lead sulfate at the bottom of the negative plates. The phenomenon has been explained [2] in terms of poor charge-acceptance of the negative plates. In our study, however, the discovery of large, internal temperature gradients as a result of high charge/discharge currents supports the proposition of an additional hypothesis, as follows.

It is well known that if two batteries in parallel are operated at significantly different temperatures, the hotter battery will experience the greater utilization of active material during discharge. The same unit will also accept a higher amount of charge. Given that the top and bottom regions of a battery plate are effectively in parallel, it follows that if they are at different temperatures, they will experience different extents of active-material utilization

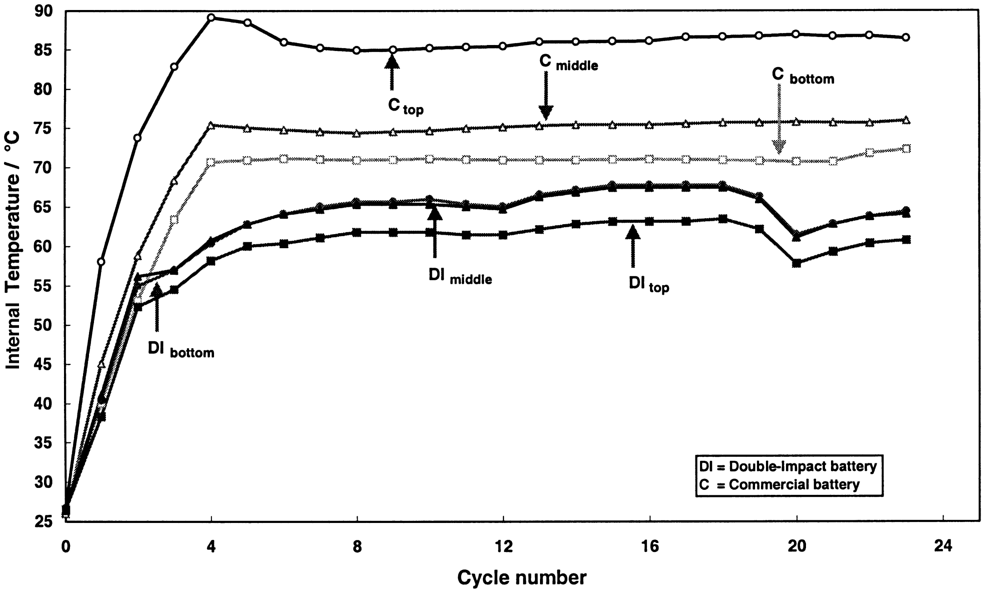

Fig. 4. Temperature performance of Double-Impact™ and commercial batteries under simulated PSoC/fast-charge EV duty ($6C_1$ charge rate).

during discharge. Also, the hotter locations will experience a higher degree of overcharge relative to the cooler areas. We suggest that this situation will lead to undercharging, and hence sulfation, of the cooler regions. The Double-Impact™ battery does not develop significant temperature gradients during either HEV or PSoC/fast-charge EV duty and, therefore, is not expected to suffer from preferential sulfation.

3. Outcomes and conclusions

An advanced design of VRLA battery has been developed for use in a novel HEV. The unit — the Double-Impact™ battery — has current take-offs at both ends of each plate. Its performance, and that of a comparable, state-of-the-art commercial unit has been evaluated under HEV and PSoC/fast-charge EV conditions. Under the former duty, the Double-Impact™ battery operates at a much reduced temperature and delivers more cycles before requiring equalization. The performance advantage of the Double-Impact™ battery is even more dramatic under the severe PSoC/fast-charge EV schedule, which was employed in these studies — to date, it has delivered 220 cycles with an end-of-discharge voltage, which is still well above the cut-off limit, compared with only 100 cycles that can be obtained from the commercial battery. Moreover, the internal temperature of the Double-Impact™ battery remains uniform throughout at a maximum of 65°C. By contrast, the maximum internal temperature at the bottom, middle and top of the commercial battery reached 70°C, 75°C and 90°C, respectively.

The overall performance of the Double-Impact™ battery suggests that this design will ameliorate the maintenance and life problems experienced to date with the operation of lead–acid batteries under HEV and PSoC/fast-charge EV conditions.

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