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The UltraBattery—A new battery design for a new beginning in hybrid electric vehicle energy storage[☆]

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ABSTRACT

The UltraBattery, developed by CSIRO Energy Technology in Australia, is a hybrid energy storage device which combines an asymmetric super-capacitor and a lead–acid battery in single unit cells. This takes the best from both technologies without the need for extra, expensive electronic controls. The capacitor enhances the power and lifespan of the lead–acid battery as it acts as a buffer during high-rate discharging and charging, thus enabling it to provide and absorb charge rapidly during vehicle acceleration and braking.

The initial performance of the prototype UltraBatteries was evaluated according to the US FreedomCAR targets and was shown to meet or exceed these in terms of power, available energy, cold cranking and self-discharge set for both minimum and maximum power-assist hybrid electric vehicles (HEVs). Other laboratory cycling tests showed a fourfold improvement over previous state-of-the-art lead–acid batteries under the RHOLAB test profile and better life than commercial nickel/metal hydride (NiMH) cells used in a Honda Insight when tested under the EUCAR HEV profile.

As a result of this work, a set of twelve 12 V modules was built by The Furukawa Battery Co., Ltd. in Japan and were fitted into a Honda Insight instead of the NiMH battery by Provector Ltd. The battery pack was fitted with full monitoring and control capabilities and the car was tested at Millbrook Proving Ground under a General Motors road test simulation cycle for an initial target of 50 000 miles which was extended to 100 000 miles. This was completed on 15th January 2008 without any battery problems. Furthermore, the whole test was completed without the need for any conditioning or equalisation of the battery pack.

1. Introduction

Currently, candidate energy storage systems for hybrid electric vehicle (HEV) applications include valve-regulated lead–acid (VRLA), nickel/metal hydride (NiMH), rechargeable lithium batteries, and the super-capacitor. Since a super-capacitor has high power, but low energy, this device alone cannot be used in full- and plug-in-HEVs in practice. It is obvious that the VRLA battery has great advantages in terms of low initial (capital) cost, a well established manufacturing base, distribution networks and high recycling efficiency compared to the other competitive technologies at their present stage of development. Nevertheless, the running cost of the normally available VRLA battery is expensive because of its short service life. The VRLA battery under HEV applications must be operated under high-rate discharge and charge regime within a certain state-of-charge (SoC) window, i.e., 30–70% SoC. This is because the battery cannot deliver the required cranking current when the SoC is below 30%. On the other hand, the battery cannot accept charge efficiently either from regenerative braking or from engine charging when the SoC is above 70%. Under such applications, the VRLA battery fails prematurely due to the sulfation of the negative plates [1]. The negative plates suffer from a progressive build-up of 'hard' lead sulfate on the surface, i.e., lead sulfate which is difficult to recharge. The accumulation of lead sulfate markedly reduces the effective surface-area to such extent that the plate can no longer deliver and accept the power required by engine cranking, acceleration, and regenerative braking. To address this problem, CSIRO Energy Technology has developed an advanced UltraBattery, which combines a super-capacitor, and a lead–acid battery in one unit cell (Fig. 1), taking the best from both technologies without the need for extra electronic controls [2,3]. The capacitor electrode acts as a buffer to share the discharge and charge currents with the lead–acid negative plate and thus prevents it being discharged and charged at the full rates required by the HEV duty. This technology now is

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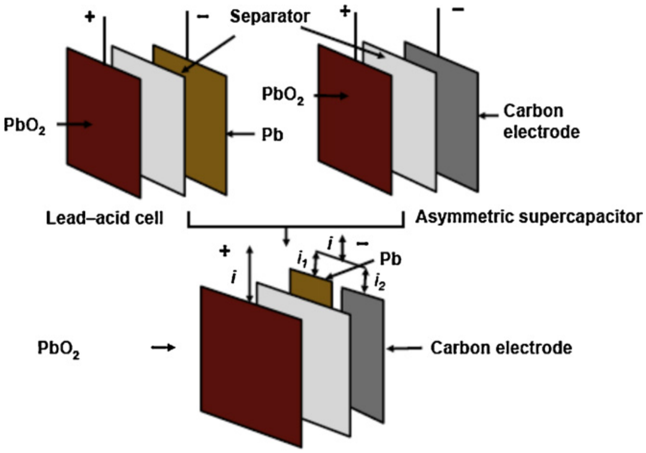

Fig. 1. Schematic view of the UltraBattery.

in the 'preproduction' stage and prototypes are being produced for evaluation in the laboratories and demonstration in the HEVs.

2. Experimental

12 V prototype UltraBatteries were produced at Furukawa Plants and subjected to quality-control checks in terms of initial capacity and internal resistance. The batteries with similar capacity and internal resistance were selected for the subsequent laboratory tests and field trial. For the laboratory tests, the initial performance of UltraBatteries was evaluated in terms of capacity, power, cold cranking and self-discharge. These tests were based upon the US FreedomCAR Battery Test Manual (DOE/ID-11069, October 2003). On the other hand, the cycling performance of UltraBatteries was evaluated using: (i) a simplified discharge and charge profile to simulate the micro-HEV driving conditions; (ii) a 42-V profile to simulate the mild HEV driving conditions [4]; (iii) EUCAR and RHOLAB profiles to simulate the medium HEV driving conditions [5,6]. For the field trial, twelve prototype UltraBatteries were delivered to Provector Limited, UK for a field trial in a Honda Insight HEV.

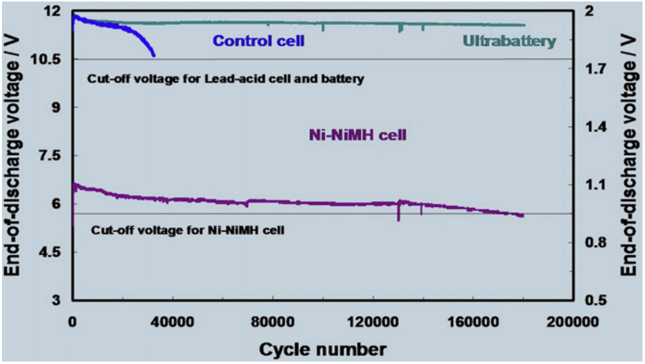

Fig. 2. UltraBattery cycling vs NiMH under the EUCAR power-assist profile.

3. Results and discussion

The initial performance of the UltraBattery is given in Table 1. According to the US FreedomCAR protocol, the discharge and charge power are 25 and 20 kW set for the minimum power-assist system and 40 and 35 kW set for the maximum power-assist system, respectively. Results show that the UltraBattery, operating in a 80–30% SoC window, will meet or exceed the discharge and charge power required by the minimum and maximum power-assist systems. Clearly, with the integration of the super-capacitor electrode, the operational range of the UltraBattery is between 80% and 30% SoC, instead of 70–30% SoC as usually used for the VRLA battery. The UltraBattery technology has met or exceeded the targets of available energy, cold cranking and self-discharge required by the minimum and maximum power-assist systems. For self-discharge evaluation, it has been found that allowing the UltraBattery to stand under 30 °C at open-circuit and partial-state-of-charge conditions for 7 days may not be enough to cause any apparent self-discharge of the battery even though the test has been repeated three times

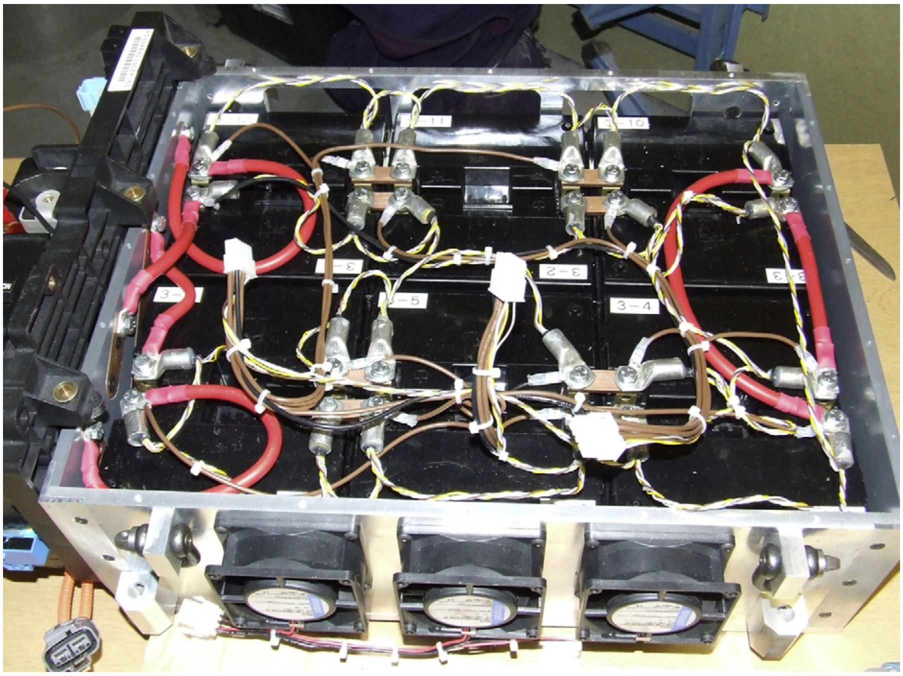

Fig. 3. Assembled battery pack–Honda Junction Board on the left.

Table 1
Initial performance of the UltraBatteries.

Characteristics	Units	Minimum power-assist	Maximum power-assist
Pulse discharge power (10 s)	kW	25	40
Regenerative pulse power (10 s)	kW	20	35
Operating state-of-charge window	%	80–30	80–30
Available energy	Wh	940 (goal = 300)	1500 (goal = 500)
Cold cranking	kW	5.4 (1st), 5.2 (2nd), 5.1 (3rd) (goal = 5)	10.5 (1st), 11.3 (2nd), 11.3 (3rd) (goal = 7)
Self-discharge	Wh day^{-1}		
Measurement at 30 °C, 7 days		+3.90 (1st), +6.38 (2nd), +4.28 (3rd) (goal = −50)	+6.51 (1st), +10.64 (2nd), +7.14 (3rd) (goal = −50)
Measurement at 40 °C, 23 days		−7.42	−12.37

Table 2
Cycling performance of the UltraBatteries.

Test profiles	Units	Battery types		
		Control VRLA battery	NiMH cell	UltraBattery
Simplified discharge and charge profile at 3 C rate (ToCV = 2.5 V; CoV = 1.75 V)	Cycles	11 000–13 000	72 000	75 000
Simplified discharge and charge profile at 2 C rate (ToCV = 2.83 V; CoV = 1.83 V)	Cycles	4 200	–	18 000
42-V profile	Cycles	17 500	–	165 000
EUCAR profile	Cycles	34 000–72 000	180 000	240 000 (1st, on test) 220 000 (2nd, failed)
RHOLAB profile	Cycles	150–180		750–1 100

(see Table 1, plus sign shows energy gain, while minus sign indicates energy loss). Therefore, the test was performed again by allowing the battery to stand in an open-circuit condition for 23 days, instead of 7 days and under 40 °C, instead of 30 °C.

The cycling performance of the UltraBattery is given in Table 2. The prototype UltraBatteries show significantly longer cycling performance than the control VRLA batteries. More importantly, to date, the cycling performance of the UltraBatteries is proven to be comparable, or superior, to that of NiMH cells where side by side testing has been conducted (Fig. 2).

4. Vehicle demonstration

The conversion of the Insight from its NiMH battery to the UltraBattery was done by Provector Ltd. utilising the experience gained from converting the Insight in the RHOLAB Project [5]. However, the electronics have been much refined since this earlier project. The UltraBattery is relatively compact and the battery of 12 × 12 V modules was built into a container which was designed to mate with the original Honda junction board for the power electronics (Fig. 3). The battery pack was fitted with cooling fans and a complete battery management and data logging system. The completed battery fitted into the exact space utilised by the 144 V NiMH battery (Fig. 4). The vehicle started testing at Millbrook in April 2007 and is pictured in Fig. 5 on the track during the test.

With the combination of having a ‘generation 2’ battery and updated electronics, this vehicle has performed outstandingly in its test—frequently running a three shift day with very stable battery voltages and temperature. In fact the vehicle reached its initial target of 50 000 miles a day later than the RHOLAB car and with-

Fig. 4. The UltraBattery in place.

out any equalisation or conditioning of the battery being carried out.

As a result of this performance, it was decided to extend the test to 100 000 miles—way beyond normal warranty distance for the NiMH battery. This milestone for advanced lead–acid batteries was reached on 15th January 2008. Thus the vehicle had covered the 100 000 miles in barely 9 months. Also, at the end of the test, the battery had still not been equalised or conditioned.

4.1. The test cycle

As well as being equipped with the battery management system the vehicle has very comprehensive data logging system, capturing information on items such as module voltage, current, state of charge and battery temperatures as often as four times per second. Data is also recorded from the vehicle's on-board diagnostic system (OBD) as well the Global Positioning System (GPS). Thus as well as recording any abnormalities in the data, it is possible to locate the vehicle's position and also how it was being driven—by looking at throttle position, engine rpm etc. By logging all this information a massive amount of data has been obtained on how the battery behaves under the hybrid duty cycle. The actual test cycle used is a proven OEM motorway simulation driving cycle on the Millbrook high speed bowl which is capable of moving the battery state-of-charge around as well as putting on the miles quickly to keep testing costs realistic. This is illustrated in Fig. 6 and Fig. 7 shows a recorded GPS speed trace of the test (including an unscheduled stop).

The test cycle is described as follows and begins at the entrance to the high speed bowl or at the end of the previous cycle. The 'BRAKE PADs' referred to are visible stopping areas on the inside of the track.

Accelerate to 30 mph (48 km h^{-1}) and join the HIGH SPEED CIRCUIT.
After joining the HIGH SPEED CIRCUIT accelerate to 65 mph (105 km h^{-1}). At the end of BRAKE PAD 1 overrun to 60 mph (97 km h^{-1}) then accelerate to 70 mph (113 km h^{-1}).
At the end of BRAKE PAD 2 overrun to 65 mph (105 km h^{-1}) then accelerate to 75 mph (121 km h^{-1}).
At the end of BRAKE PAD 3 overrun to 70 mph (113 km h^{-1}) then accelerate to 80 mph (129 km h^{-1}).
At the end of BRAKE PAD 4 overrun to 60 mph (97 km h^{-1}), light braking as necessary, then accelerate to 70 mph (113 km h^{-1}) and hold.
Hold 70 mph (113 km h^{-1}) for Laps 2 and 3.
At the start of BRAKE PAD 2 on Lap 4 overrun to 60 mph (97 km h^{-1}).

Fig. 5. The UltraBattery Insight under test at Millbrook.

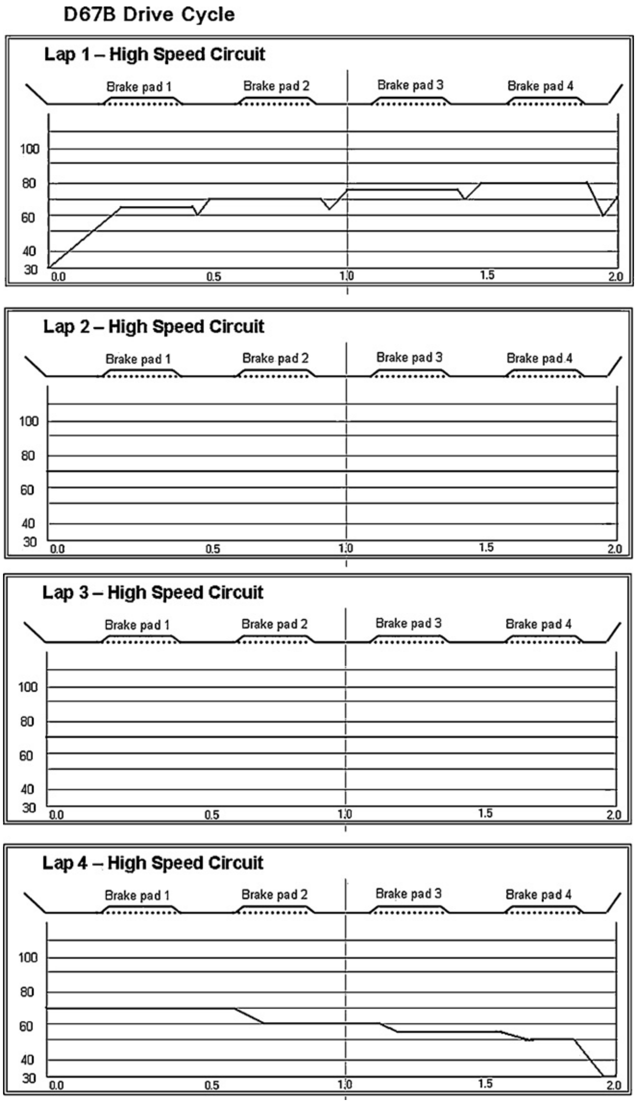

Fig. 6. The drive cycle.

Hold 60 mph (97 km h^{-1}) until the start of BRAKE PAD 3. At the start of BRAKE PAD 3 overrun to 55 mph (88 km h^{-1}).
Hold 55 mph (88 km h^{-1}) until the start of BRAKE PAD 4. At the start of BRAKE PAD 4 overrun to 50 mph (80 km h^{-1}).
Hold 50 mph (80 km h^{-1}) until the end of BRAKE PAD 4 and then brake to exit the HIGH SPEED CIRCUIT at the end of Lap 4 at 30 mph (48 km h^{-1}) or continue into next module.

The data monitoring has also been such that it has been easily possible to identify differences in driver skills in adhering to the test cycle—or, on occasions where driver errors have resulted in issues with the vehicle.

4.2. Typical test data

Fig. 8 shows module maximum and minimum voltages for each of the 12 modules plotted on top of each other during a run. It can be seen that the module voltages overlay each other well, indicating uniform operation. Fig. 9 shows the maximum and minimum currents plotted in the same way while Fig. 10 shows the state of charge of each of the 12 modules during a run.

It is quite surprising how uniformly these are tracking as it is more common for batteries in a string to diverge in SoC

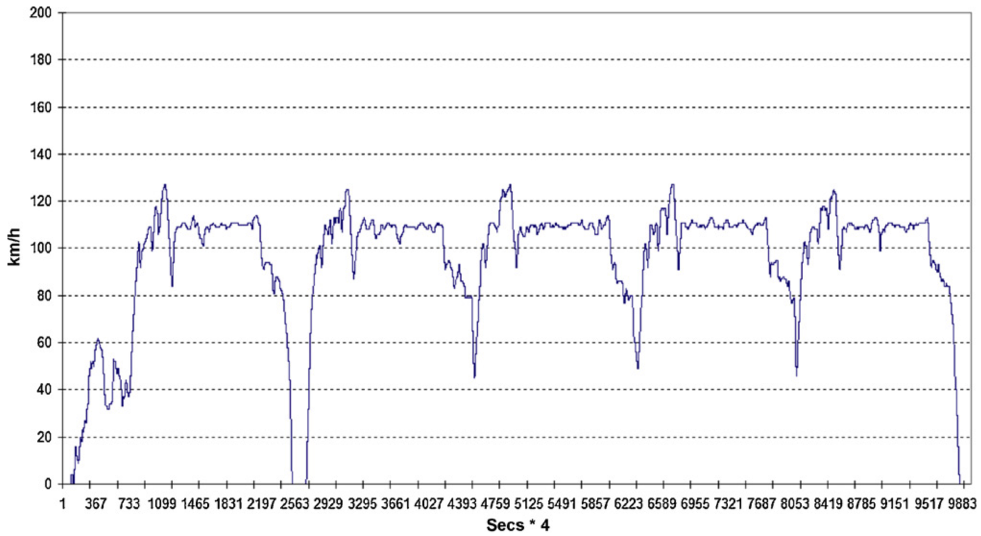

Fig. 7. A GPS speed plot.

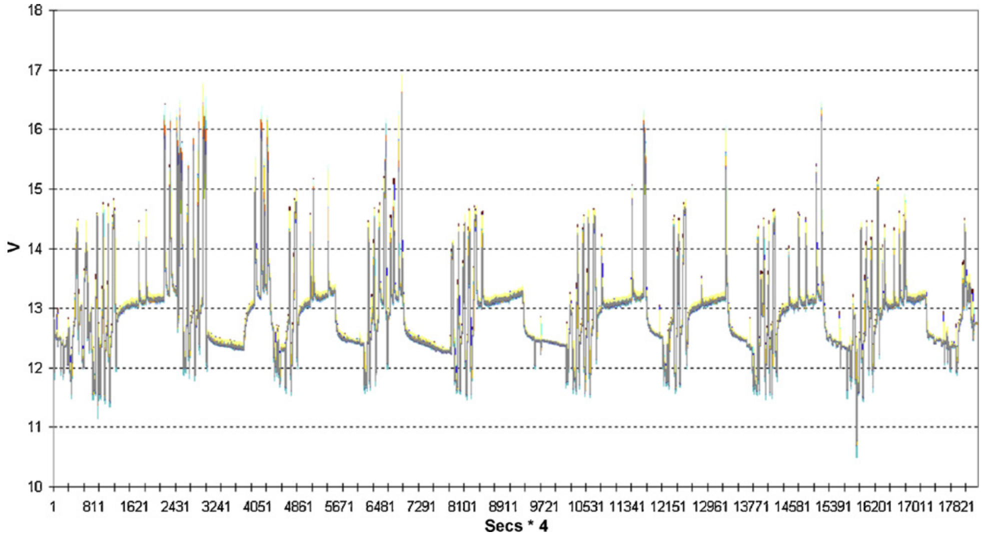

Fig. 8. Maximum and minimum module voltages during a test.

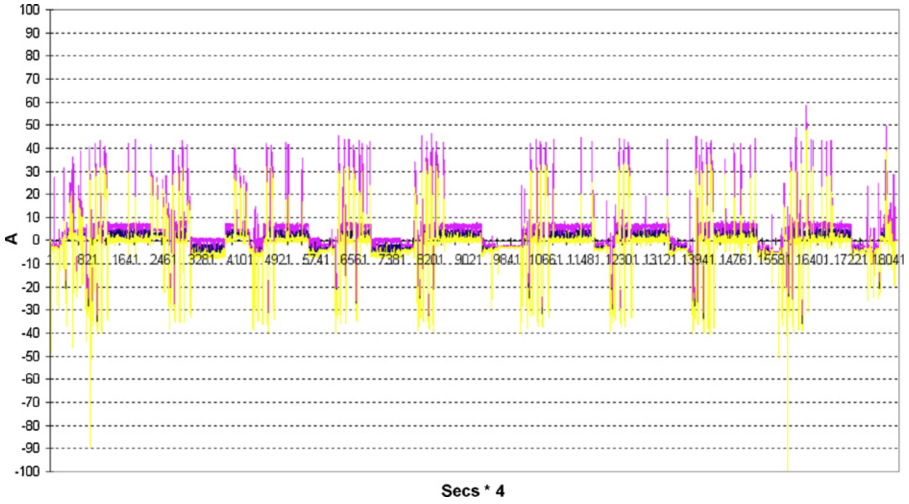

Fig. 9. Maximum and minimum currents plotted during a test run. Assist currents are positive.

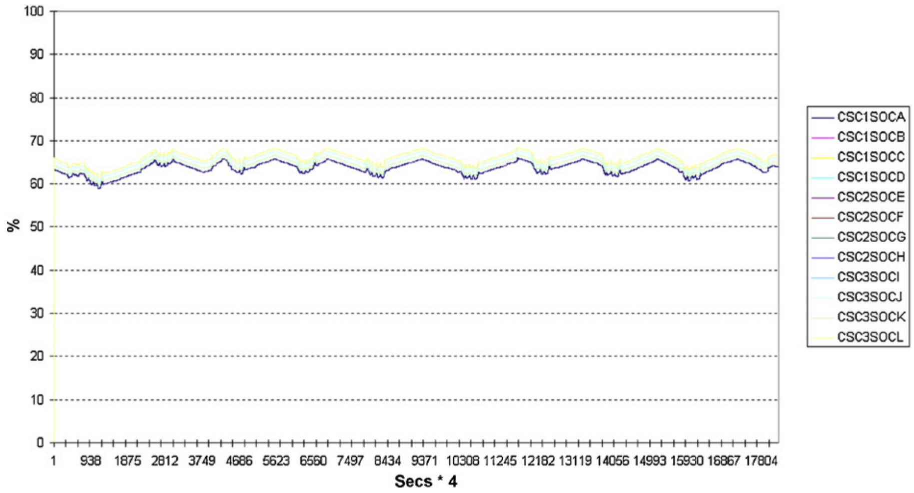

Fig. 10. Variations in the state-of-charge of the modules during a test run.

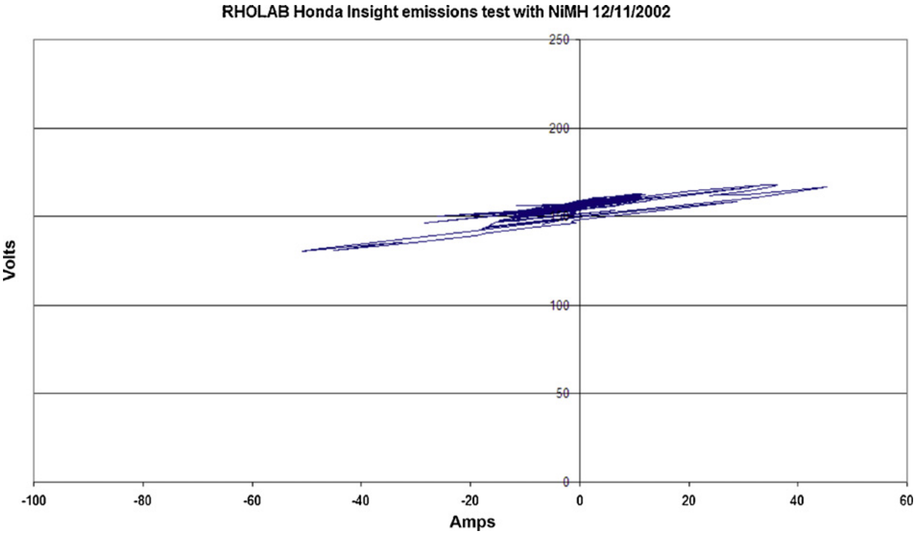

Fig. 11. Voltage vs current plot for a NiMH battery.

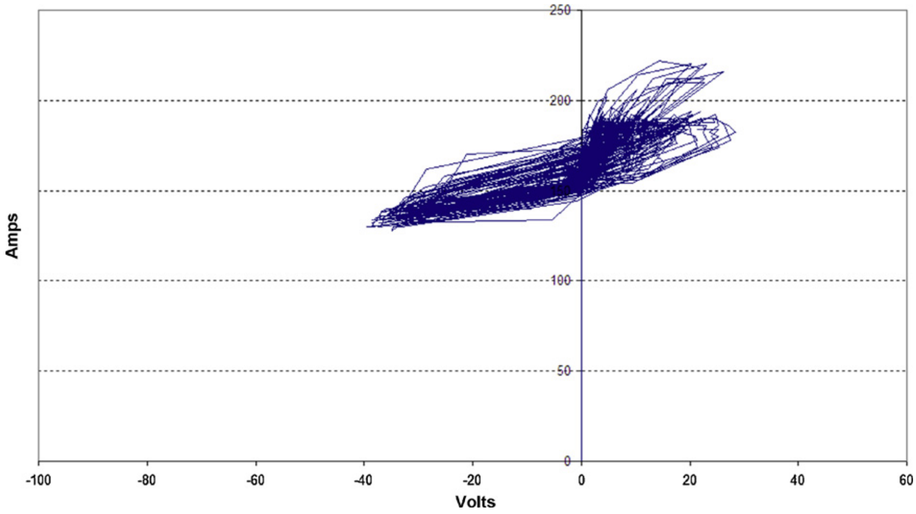

Fig. 12. Voltage vs current plot for the RHOLAB battery at 70% SoC.

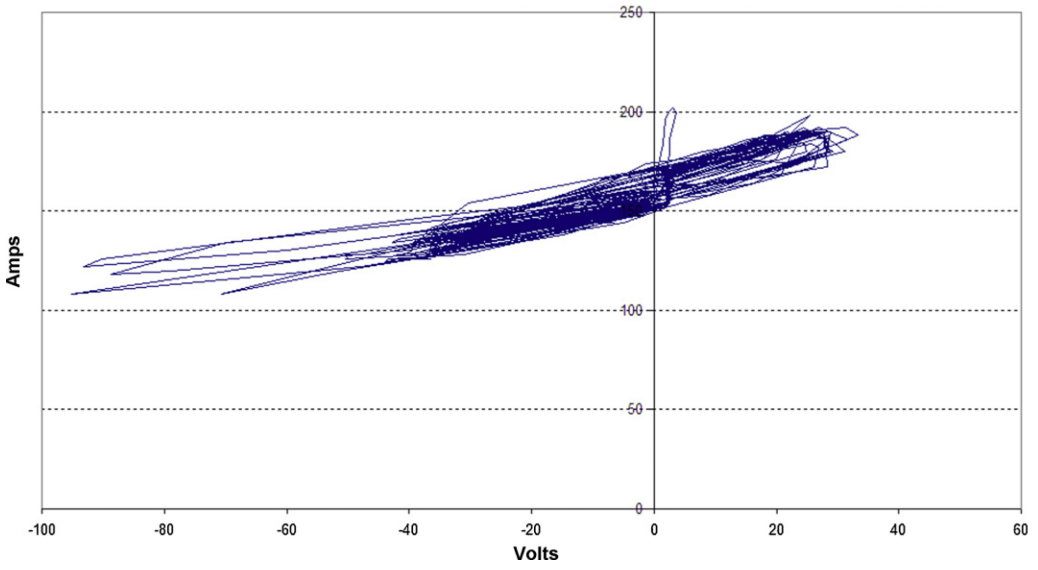

Fig. 13. Voltage vs current plot for the RHOLAB battery at 50% SoC.

quite rapidly as was discussed in the paper given to EET2007 [7] when the ISOTEST programme was discussed. With this trial of the UltraBattery, the modules were within 1.5% of each other at the end of the test—a truly remarkable result bearing in mind no equalization or conditioning of the batteries took place at all.

The paper given at EET2007 [7] looked at the voltage vs current plots for NiMH batteries as against the lead–acid batteries used in the RHOLAB batteries. It was stated that a key objective when replacing the NiMH battery is to maintain a flat curve in these plots. This is particularly important if the control software in the vehicle's Motor Control Module cannot be modified, as in these projects, but also it is a measure of system efficiency. The curve for the standard Honda Insight NiMH battery recorded on an emissions test is shown in Fig. 11.

It is interesting to look at comparable plots for the RHOLAB battery. When operated at a state-of-charge of around 70%, the lead–acid battery exhibits higher voltages and higher apparent impedance on charging as seen in Fig. 12. It is undesirable if the voltage exceeds 2.5 V per cell for more than a few seconds at a time as this can act to dry out the cell. However, when operated at a rather lower state-of-charge the RHOLAB cells have a characteristic which is very like the NiMH battery with no undesirable voltage peaks and a flat characteristic as seen in Fig. 13.

As can be seen in Fig. 14, the characteristic curve for the UltraBattery is rather different in that there are voltage peaks during the recharge events. However, it is felt that one effect of the capacitive negative plate is to make the battery less susceptible to problems associated with these high voltages, such as dry out. The curve is very flat over the rest of the current range, and on many occasions at high charge currents, and is much closer to NiMH-like performance than the earlier batteries.

The vehicle ran well during the testing and no problems with the car during running were battery-related. The overall fuel consumption during the test was 4.73 l/100 km—a fraction under 60 mpg. It is not possible to relate this performance to the vehicle with

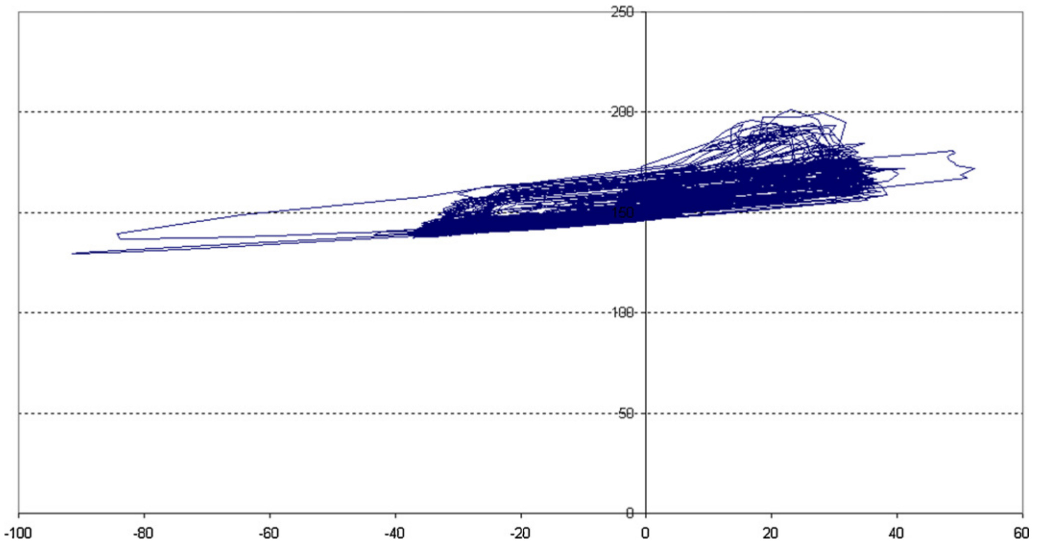

Fig. 14. Voltage vs current plot for the UltraBattery at about 65% SoC.

the NiMH battery because, when the original RHOLAB car was investigated at Millbrook, it was to a different test cycle reflecting the need to gather a wide range of data in as short a period as possible.

5. Conclusions

Laboratory testing of the UltraBattery had suggested that this technology represented a step change in lead–acid battery performance, particularly in micro- and mild-hybrid vehicle applications. This improved performance offered by the UltraBattery has been demonstrated in prolonged testing in hybrid vehicle with convincing results. As a result of its much lower cost than other electro-chemical systems, the UltraBattery is set to become an attractive option in future thinking for micro and mild HEV design.

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References

[1] L.T. Lam, N.P. Haigh, C.G. Phyland, A.J. Urban, J. Power Sources 133 (2004) 126–134.
[2] International Patent Application No. PCT/AU2004/001262, 2004.
[3] L.T. Lam, R. Louey, J. Power Sources 158 (2006) 1140–1148.
[4] T. Noda, K. Hata, K. Yamanaka, M. Tsubota, Paper Presented at the Ninth Asian Battery Conference, Bali, Indonesia, September, 2001.
[5] A. Cooper, J. Power Sources 133 (2004) 116–125.
[6] F. Trinidad, C. Gimeno, J. Gutierrez, R. Ruiz, J. Sainz, J. Valenciano, J. Power Sources 116 (2003) 128–140.
[7] A. Cooper, M. Kellaway, B. Bonnet, J. Marco, N. Vaughan, The Demonstration of New Generation Lead–Acid Batteries in Hybrid Electric Vehicles, EET, Brussels, May 2007.