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Short communication

Further demonstration of the VRLA-type UltraBattery under medium-HEV duty and development of the flooded-type UltraBattery for micro-HEV applications

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ABSTRACT

The UltraBattery has been invented by the CSIRO Energy Technology in Australia and has been developed and produced by the Furukawa Battery Co., Ltd., Japan. This battery is a hybrid energy storage device which combines a super capacitor and a lead-acid battery in single unit cells, taking the best from both technologies without the need of 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 laboratory results of the prototype valve-regulated UltraBatteries show that the capacity, power, available energy, cold cranking and self-discharge of these batteries have met, or exceeded, all the respective performance targets set for both minimum and maximum power-assist HEVs. The cycling performance of the UltraBatteries under micro-, mild- and full-HEV duties is at least four times longer than that of the state-of-the-art lead-acid batteries. Importantly, the cycling performance of UltraBatteries is proven to be comparable or even better than that of the Ni-MH cells. On the other hand, the field trial of UltraBatteries in the Honda Insight HEV shows that the vehicle has surpassed 170,000 km and the batteries are still in a healthy condition. Furthermore, the UltraBatteries demonstrate very good acceptance of the charge from regenerative braking even at high state-of-charge, e.g., 70% during driving. Therefore, no equalization charge is required for the UltraBatteries during field trial. The HEV powered by UltraBatteries gives slightly higher fuel consumption (cf., 4.16 with 4.05 L/100 km) and CO_2 emissions (cf., 98.8 with 96 g km^{-1}) compared with that by Ni-MH cells. There are no differences in driving experience between the Honda Insight powered by UltraBatteries and by Ni-MH cells. Given such comparable performance, the UltraBattery pack costs considerably less – only 20–40% of that of the Ni-MH pack by one estimate. In parallel with the field trial, a similar 144-V valve-regulated UltraBattery pack was also evaluated under simulated medium-HEV duty in our laboratories.

In this study, the laboratory performance of the 144-V valve-regulated UltraBattery pack under simulated medium-HEV duty and that of the recently developed flooded-type UltraBattery under micro-HEV duty will be discussed. The flooded-type UltraBattery is expected to be favorable to the micro-HEVs because of reduced cost compared with the equivalent valve-regulated counterpart.

1. Introduction

Nowadays, there is a growing concern about global warming and the limited supply of fossil fuel. As a result, there is a strong push for automobiles with reduced CO_2 emissions and improved fuel economy. In Europe, for example, various governments demand automakers to decrease CO_2 emissions from current value of about 160 g for every 1 km driven to 140 g by 2008 and this is expected to decrease further to 120 g km^{-1} by 2012. Likewise, the Japanese government requires automakers to improve fuel economy from the present value of 13.6 km L^{-1} to 17.2 km L^{-1} by 2015. With such requirements, clearly, the micro-hybrid electric vehicles (micro-HEVs), which have new features including idling-stop and regenerative braking in addition to the alternator controlling will become the main stream in the near future.

Similar to the conventional automobile, the micro-HEV also has only one 12-V lead-acid starter battery. Nevertheless, there are great differences in the service conditions of the battery between these two vehicles. Accordingly, the Japanese Society of Automotive Engineers and the Battery Association have jointly established a lead-acid starter battery standard for the idling-stop micro-HEV applications. In this standard, the battery endurance test procedure is also included. At the 12th Asian Battery Conference in Shanghai, China, we presented the performance of improved flooded

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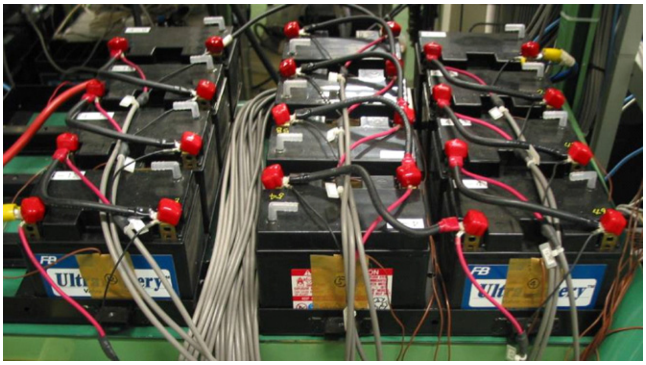

Fig. 1. A 144-V VR UltraBattery pack tested under the simulated medium-HEV duty.

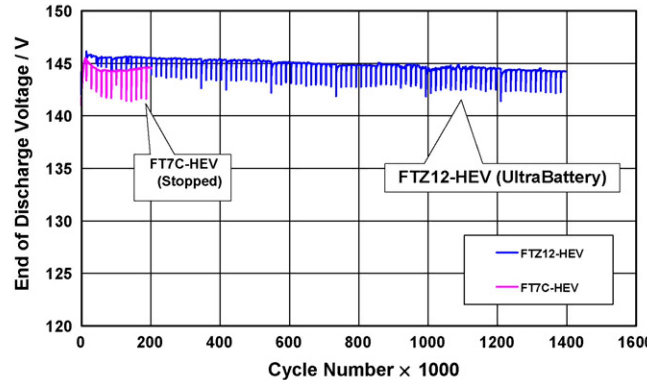

Fig. 2. Behaviour of discharge voltages of the 144-V conventional VRLA battery and VR UltraBattery packs under the simulated, medium-HEV test.

SLI battery for idling-stop micro-HEV applications. Results showed that the improved flooded SLI battery has achieved 65,000 cycles under the idling-stop profile, this significantly exceeds the target of 30,000 cycles set by the standard.

The 12-V, 6.7 Ah at the 1-h rate, valve-regulated (VR) UltraBattery – a combined lead-acid and supercapacitor hybrid energy storage device – has proven to have excellent high-rate, partial state-of-charge (HRPSoC) durability in the test run of the 144-V Honda Insight medium-HEV at Millbrook Proving Ground [1–11]. The Honda Insight medium-HEV has surpassed 170,000 km and the UltraBattery pack is still in a healthy condition.

In this paper, the laboratory performance of the VR UltraBattery pack under simulated medium-HEV duty and a flooded UltraBattery design under micro-HEV duty will be discussed. The flooded UltraBattery, which is a combined improved flooded SLI battery feature and UltraBattery technology, is expected to be favorable to the micro-HEVs because of reduced cost compared with the valve-regulated counterpart [12,13].

2. Performance of the 144-V UltraBattery string

Twelve, 12-V VR UltraBatteries with 5-h capacity of 8.5 Ah were connected in series as shown in Fig. 1. The battery pack was then cycled under a simulated, medium-HEV profile. This profile composes of 10 cycles and each cycle comprises several discharge and charge steps with different rates and duration. The average time and the discharge–charge window of one cycle in the profile are 33 s and about 0.35% of the nominal 5-h capacity, respectively. Furthermore, the charge-to-discharge ratio of each cycle is less than 101%. After fully charged, the UltraBattery pack was discharged at 5-h rate to 60% SoC of the nominal 5-h capacity and then subjected repetitively to the above profile for 5 days, followed by a 2 days rest at open-circuit. The test, which composes of 5 days cycling and 2 days rest, was then repeated. During cycling, no conditioning and/or equalization charge were conducted and the battery temperature increased to 36–38 °C. The cycle life target of this test is 200,000 cycles.

The changes in the discharge voltage of the conventional 144-V VRLA battery pack and 144-V VR UltraBattery pack are shown in Fig. 2. The UltraBattery pack has already passed 1,400,000 cycles, which are seven times greater than the target value, i.e., 200,000 cycles and the time has taken more than 2 years since the start of the test. Nevertheless, no major decrease in the pack voltage is observed even though no conditioning and/or equalization charge was performed during the test. The capacity turnover of the UltraBattery pack has reached about 5000 times. At present, the test is still ongoing. On the other hand, the conventional VRLA battery pack has completed the test, since the pack reached the target of 200,000 cycles.

Fig. 3 shows the changes in discharge voltages of individual, 12-V batteries in the 144-V conventional VRLA and VR UltraBattery strings. The voltage deviations between individual batteries in the conventional VRLA string were rapidly enlarged during the initial 200,000 cycles and therefore, the conventional battery pack was removed from the test. On the other hand, it is clear that voltage deviations between the individual UltraBatteries were small even though the UltraBattery pack has undergone for 1,400,000 cycles. The reason for the suppression of voltage deviations in the UltraBattery string is considered to be the greater charge acceptance of the capacitor components in these batteries. The UltraBattery pack will be kept on cycling until the pack voltage reaches 120 V.

3. Performance of the flooded-electrolyte UltraBattery

Prototype flooded 2-V UltraCell and 12-V UltraBattery with JIS D23 size were made by the combining of the supercapacitor and the flooded ISS battery into a single unit cell. The constitutions of UltraBattery, ISS battery and conventional battery are shown in Table 1. The initial performance and the cycle life of these batteries were evaluated and compared with that of the ISS and conventional batteries. For cycle life evaluation, the hot J240 test at 60 °C and 75 °C, micro-HEV cycle life test (SBA-S-0101), simplified PSoC cycle life test, and EUCAR cycle life test were used. The simplified PSoC cycle life test was performed in such a way that the charge-to-discharge ratio was deliberately set to less than 100% in order to simulate the batteries under insufficient charge conditions. In the EUCAR cycle life test, conditioning charges were not performed at all during the test.

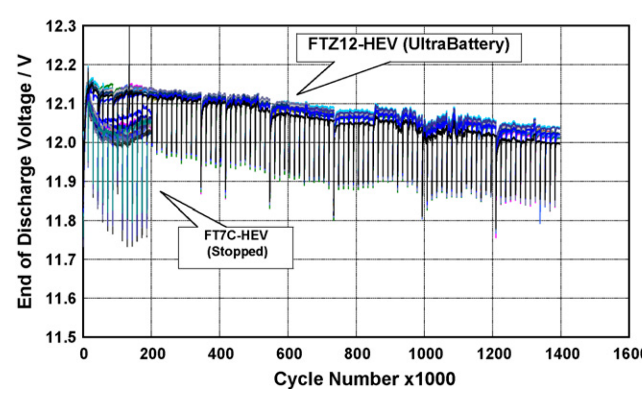

Fig. 3. Changes in the discharge voltages of individual conventional VRLA batteries and VR UltraBatteries in the respective 144-V strings during testing under the simulated, medium-HEV duty.

Table 1
Constitutions of UltraBattery, ISS battery and conventional battery.

Modifications	UltraBattery	ISS battery	Conventional battery
Addition of NAM modifier and optimized carbon content of NAM to suppress NAM sulfation and lug thinning failure modes	Yes	Yes	No
Addition of PAM modifier and optimized density of PAM to suppress PAM softening	Yes	Yes	No
Using new separator to minimize stratification and PAM softening	Yes	Yes	No
Integrate capacitor electrode to increase charge acceptance	Yes	No	No

Table 2
The initial performance test results.

Test items	UltraBattery	ISS battery	Conventional battery
$L \times W \times h \times H$ (mm)	230 × 169 × 200 × 225	←	←
Weight (kg)	15.5	16.0	15.5
5 HR capacity (Ah)	48.0	48.0	50.0
−15 °C, 300 A discharge			
5th sec (V)	9.2	9.2	9.2
Discharge time (min–s)	2–14	2–04	2–12
−40 °C, 356 A discharge			
5th sec (V)	6.04	5.74	5.72
Discharge time (min–s)	27.5	17.7	20.9
Reserve capacity (min)	90	90	111
CCA (A)	450	450	500

3.1. Initial performance test

The initial performance, in terms of capacity and the low-temperature, high-rate discharge capability of the UltraBattery, ISS and conventional batteries is shown in Table 2. For the low-temperature test, the batteries were kept under the required temperatures for 16 h before commencing the discharge. The end of discharge voltage was 1.0 V per cell. Reserve capacity was measured by discharging the battery at 25 A to a voltage of 10.5 V at 25 °C. There were no large differences between the results of the UltraBattery and other batteries, except in the discharge voltage at −40 °C. The discharge voltage of the UltraBattery at −40 °C was higher than those of other batteries. This indicates that the UltraBattery is able to provide higher cranking current than the ISS and conventional batteries.

3.2. JIS D 5301 cycle life test

JIS D 5301 cycle life test, which is similar to hot J240 test, was conducted at 60 °C and 75 °C. Fig. 4 shows the discharge-voltage behaviour of UltraBattery, ISS and conventional batteries under JIS D 5301 test at 60 °C and 75 °C. It can be seen that the UltraBattery and the ISS battery give longer cycle life than the conventional battery at 75 °C. Since the battery failure under JIS D 5301 test at 75 °C is due to the positive active material shedding and grid corrosion, there is no major difference in cycle life between the UltraBattery and the ISS battery. At 60 °C, the cycle life of UltraBattery is longer than that of the ISS battery. This indicates that the UltraBattery also has superior performance under high temperature overcharge conditions.

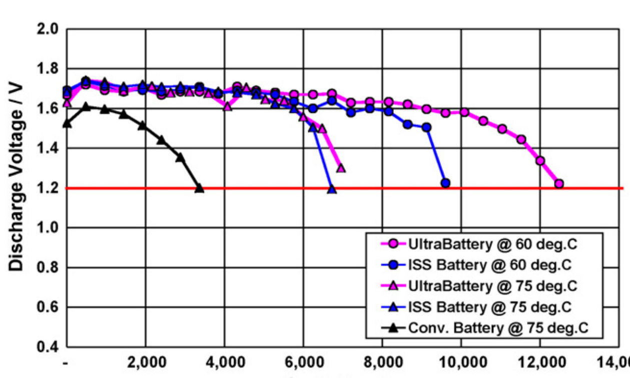

Fig. 4. Change in cell voltage during JIS D 5301 test at 60 °C and 75 °C.

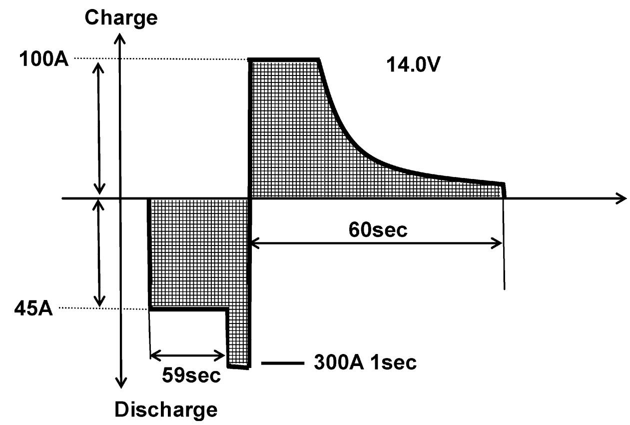

Fig. 5. Idling-stop profile for cycle life test (SBA-S-0101).

3.3. Idling-stop cycle life test (SBA-S-0101)

Fig. 5 shows the idling-stop cycle life test profile (SBA-S-0101). The batteries were subjected repetitively to this profile for 3600 times (i.e., 3600 cycles) and were then kept under open-circuit condition for 2 days. The test was carried out at the room temperature (e.g., about 23 °C). Fig. 6 shows the change in discharge voltage and specific gravity of the electrolyte of UltraBattery, ISS and conventional batteries under the simulated micro-HEV cycle life test. It can be seen that the discharge voltage of the conventional battery reached the cut-off value of 7.2 V after about 15,000 cycles and at the same time, the specific gravity of battery electrolyte decreased

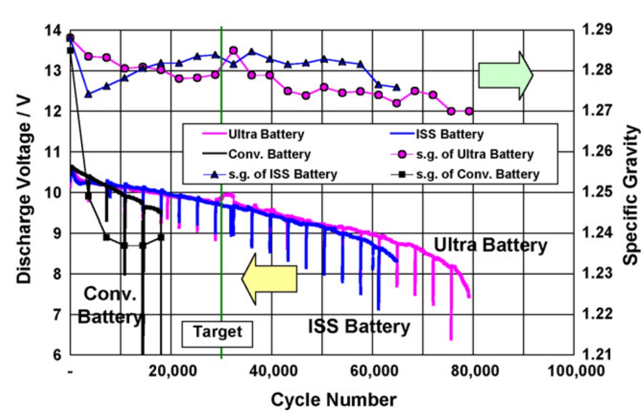

Fig. 6. Changes in discharge voltage and specific gravity during the idling-stop cycle life test.

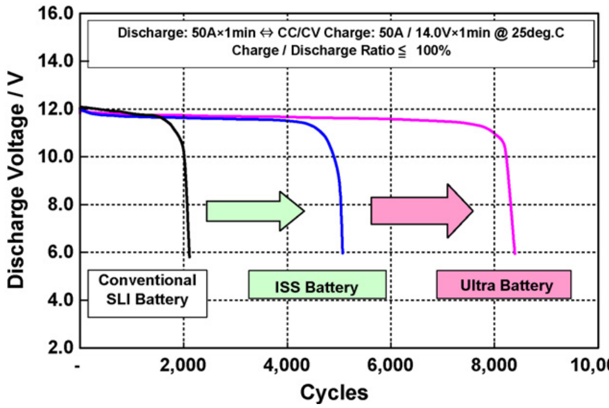

Fig. 7. Discharge-voltage behaviour under the simplified PSOC cycle life test.

to 1.240 sp.gr. This indicated that the early failure of conventional battery was due to undercharge. On the other hand, the discharge voltages of the ISS battery and UltraBattery decreased to 7.2 V after about 62,000 and 75,000 cycles, respectively. The specific gravity of electrolyte decreased to 1.275 sp.gr. for the ISS battery and 1.270 sp.gr. for the UltraBattery. These values were much higher than that of the conventional battery even though the latter two batteries had endured much longer cycle lives. This indicated that the UltraBattery and ISS battery received charge more efficiently than the conventional counterpart. In fact, the UltraBattery and ISS battery did not fail due to insufficient charging conditions. Rather, both batteries were in a state-of-overcharge. The failure mode was due to the deterioration of the positive-plate material and therefore, there was no significant difference in the cycle life between both batteries.

3.4. Simplified PSoC cycle life test

Simplified PSoC cycle life test profile comprises: (i) a discharge current of 50 A for 60 s; (ii) a constant current charge at 50 A, followed by a constant voltage charge at 14.0 V for a total duration of 60 s. Each battery was subjected to this profile repetitively until the voltage reached 6 V. Furthermore, the test was carried out at 25 °C. Fig. 7 shows the discharge-voltage behaviour under the simplified PSoC cycle life test. As mentioned in Section 3, the charge-to-discharge ratio of this test was set to slightly less than 100%. In other words, the batteries were deliberately subjected to insufficient charge conditions. The conventional battery reached the end of its life at about 2000 cycles whereas the ISS battery and UltraBattery reached the end of their lives at about 5000 and 8000 cycles, respectively. It is obvious that the UltraBattery has a superior charge acceptance than the conventional as well as the ISS battery.

3.5. EUCAR cycle life test

Fig. 8 shows the test profile of the EUCAR cycle life test. Initially, the battery was discharged at 2-h rate to 60% SoC of the 2-h capacity. The battery was then subjected of this profile repetitively until the voltage reached 1.0 V per cell. During the test, the conditioning charge was not carried out at all. Fig. 9 shows the discharge-voltage behaviour of UltraBattery, ISS and conventional batteries under the EUCAR cycle life test. It can be seen that the conventional battery reached the end of its life at about 5000 cycles, while the ISS battery achieved about 10,000 cycles. On the other hand, the UltraBattery provided the longest cycle life of about 43,000 cycles. Again, the flooded UltraBattery showed the best cycling performance under the EUCAR cycling profile.

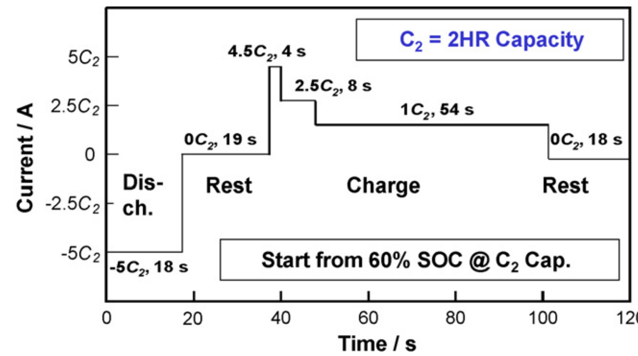

Fig. 8. EUCAR profile for cycle life test.

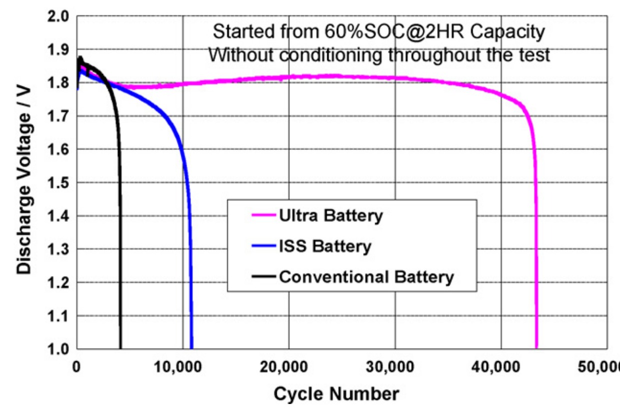

Fig. 9. Discharge-voltage behaviour under the EUCAR cycle life test.

4. Conclusions

The CSIRO and the Furukawa Battery Co., Ltd., have succeeded in development of UltraBattery either in VRLA or in flooded types. These batteries prove to be very suitable for micro- to full-HEV applications.

(i) To date, the 144-V string of VR UltraBatteries has performed 1,400,000 cycles under medium-HEV duty without requirement of conditioning and/or equalizing charge, and the number of the capacity turnover has reached about 5000 times.
(ii) The voltage deviation of individual 12-V UltraBatteries in the 144-V string is very small during the test period.
(iii) The test has undergone for more than 2 years and the batteries are still in a healthy condition.
(iv) Under JIS D 5301 cycle life test at 75 °C, the flooded-type UltraBattery give similar cycle life performance to the ISS battery, but significantly longer cycle life than the conventional battery. With reduced temperature, e.g., 60 °C, however, the UltraBattery shows longer life than the ISS battery.
(v) The flooded UltraBattery achieves significantly longer cycle life than the ISS and conventional batteries when these batteries were subjected to the PSoC cycling and under insufficient charge conditions, such as a simplified discharge-charge profile or the EUCAR profile.

The Furukawa Battery Co., Ltd., has shipped the flooded UltraBattery and the VR UltraBattery samples to automakers in Japan, Europe, and United States of America for testing.

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